AMPEX

Horizons

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ABOUT THE COVER: A vector scope reading taken from the experimental digital videotape recorder that was demonstrated in February by Ampex engineers provides the cover picture for this issue of HORIZONS. Our lead story discusses this major technical advance in detail. (Photo by Hudson Edwards, Ampex Corporation.)

AMPEX

HORIZONS

Number 2 July 1979

"The destiny of man is to be involved in creative work . . . and to make new discoveries which are of value and importance to human life and progress."
Alexander M. Poniatoff, founder of Ampex Corporation.

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Digital video recording: A progress report

BY JOACHIM P. DIERMANN and MAURICE LEMOINE

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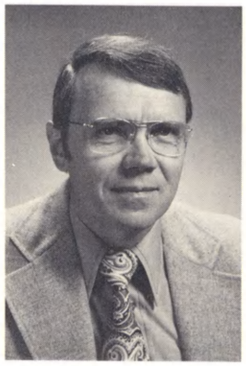

MAURICE LEMOINE is a senior staff engineer in the audio-video systems division of Ampex Corporation. Since joining the company in 1965, he has been involved in the development of digital video technology, the first digital time base corrector, the design of the VR-1200, VR-3000, HS-100, AVR-1, AVR-2 and AVR-3. Maurice holds a degree from the University of Paris.

The following article was delivered orally at the Television Conference of the Society of Motion Picture and Television Engineers, February 3, 1979, in San Francisco. The presentation included a demonstration of Ampex's experimental NTSC digital videotape recorder–the editors.

We presented a paper dealing with an analysis of choices in digital video recording at the 1978 SMPTE Winter Conference. The design objectives for this new recording technology were established against the reference point of the present one-inch analog technology, which is finding wide acceptance in the broadcast industry. The advantages and disadvantages of various digitizing methods and sampling rates, and their significance for the existing television standards of the world were weighed against one another. Digital recording of sounds and its specific problems were related to digital recording of video. Finally, the three major methods of scanning magnetic tape were analyzed with respect to their usefulness as a vehicle for digital video signals.

At the International Broadcast Conference in London last year, John Baldwin of the IBA described and demonstrated an experimental digital recorder. Today we would like to present another reference point by showing what progress Ampex has made in the laboratory to answer some of the technical questions that have been raised earlier.

The focal point of this progress report is the development of an experimental recorder, which has served and continues to serve as a tool to investigate feasibility and to gain a better understanding of how digital video signals must be treated in a magnetic recording channel. The technical approach chosen combines both innovative and practical elements. To some extent, it modifies existing technology to accommodate the different needs of a digital video signal.

The technical credit for this work goes to Mr. Maurice Lemoine, who has co-authored this paper. He is the principal engineer of a group of dedicated workers who have concerned themselves with digital video recording problems for a considerable period of time.

BASIC APPROACH

The most distinct expectation generally placed upon a digital video recorder applies to its video quality. After one generation we demand very high signal transparency. Beyond the first generation we expect picture deterioration to progress slowly enough so that impairment becomes discernible only after many more generations than is commonly accepted in the analog world. A key question facing the engineer is to what extent tape saving bit rate reduction methods can be compatible with effective error correction or concealment over many generations.

In one way or another all bit rate reduction methods imply compromises in signal transmission. We decided not to start the work relying on such a compromise, but to design a recording system that could transmit a full 8-bit PCM signal in both 625 and 525 line standards with a sampling rate of at least 3 x f_{sc} and possibly 4 x f_{sc} (Figure 1). This means a transmission capability of at least 106 Mb/second and 86 Mb/second, respectively, for the two line standards.

Obviously, such an approach demands sacrifices in tape consumption, and present usage is considerably higher than the 10 square inch/second that has become the standard of helical analog machines. This approach does not meet all the operational/economic goals of digital

video recording, rather it provides a performance benchmark at the high end from which attempts can start to find a compromise between lower tape consumption and inferior signal performance. Such compromises may consist of increased packing density on tape with more objectionable error rates that place greater demands on systems for error correction and/or concealment. They may also consist of primary bit saving schemes, such as sub-Nyquist sampling, DPCM, a mixture of both, or others.

SAMPLING RATE	2xFsc	3xFsc	4xFsc
NTSC	7.2 57.6	10.7 85.6	14.3 Ms/s 114.4 Mb/s
PAL	8.9 70.9	13.3 106.3	17.7 Ms/s 141.8 Mb/s
SECAM	/	13.3 106.3	17.7 Ms/s 141.8 Mb/s

Figure 1 Sampling and Bit-Rates

It is not clear at this time whether or not such a cost/performance trade-off is desirable or necessary. The price to be paid for lower tape consumption and the resulting weight and storage volume will be a greater dependence on tape quality resulting in a higher price per square inch and on a more complex error correction system.

COMPONENTS VERSUS COMPOSITE

It is assumed that the television plant and studio, at least within the NTSC and PAL countries, will continue to communicate on a composite level for many years even though more and more picture processing equipment may internally depend on the decoding of the video signal. Therefore, the signal system of the experimental video recorder was chosen to be of the composite type. The available data rate would be sufficient, however, to accommodate component schemes in future developments.

In the SECAM countries, plant and studio operations may be forced towards component communications sooner, due to the difficulties of handling SECAM at the studio level. An interesting and powerful 625 digital component system is being proposed by the CCETT in France. It is compatible with video recording even though its bit rate requirements are higher than would be desirable from a recording and tape usage standpoint.

RECORDING FORMAT

Several authors have stated repeatedly that the key to efficient digital video recording is the use of narrow tracks in conjunction with moderate wave lengths. The problem of following a very narrow recorded track during playback increases with track length. A transverse recorder, with its short tracks, is a particularly suitable

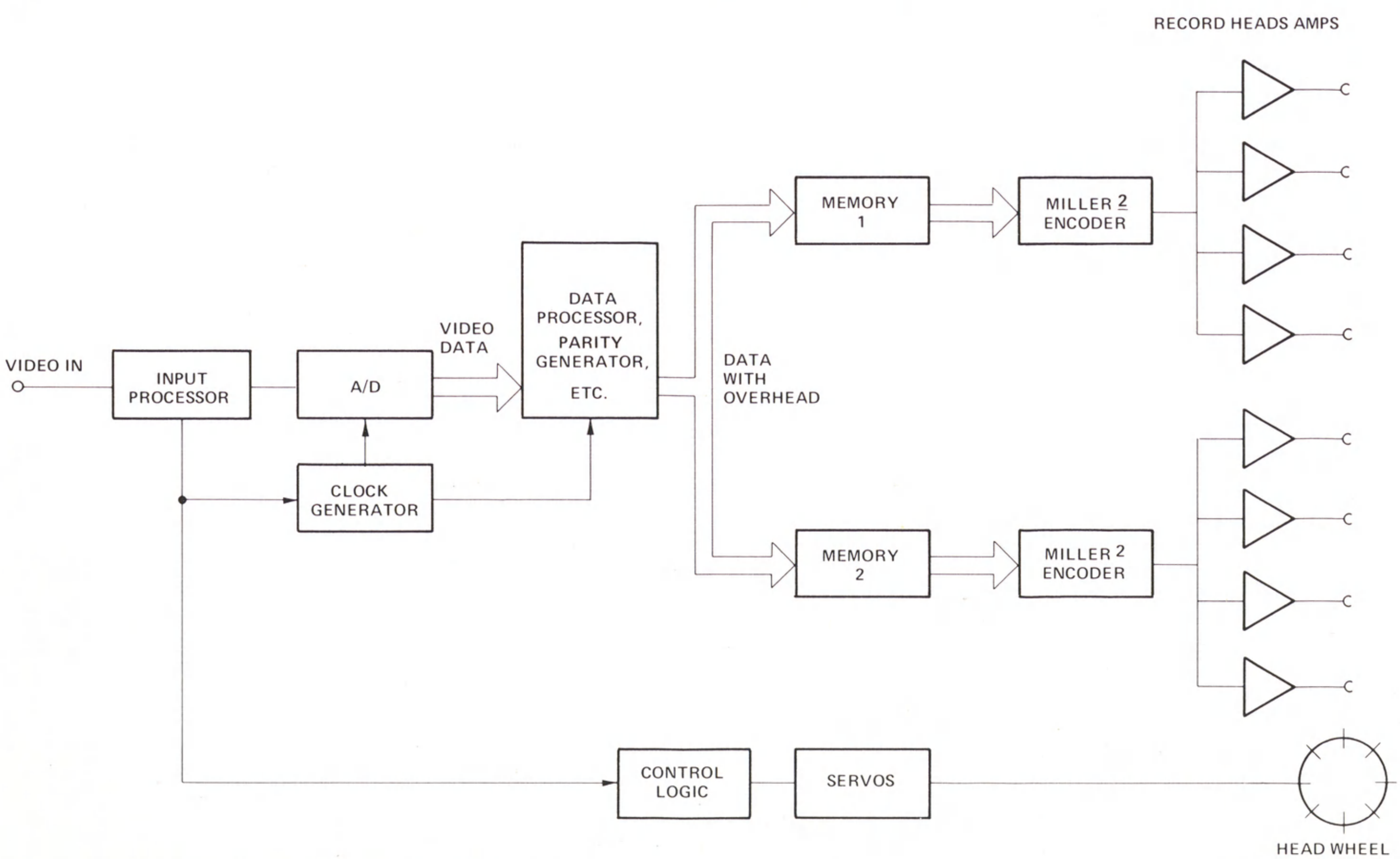

Figure 2 Digital VTR, Record Block Diagram

vehicle for writing and reading narrow tracks. For this reason, a two-inch quadruplex scanning system was chosen to be the basic experimental vehicle, even though the word "quadruplex," as will be shown, is no longer appropriate. With its two-inch track length, it performs very well down to the narrow track width required, and suits the purpose of our experimentation.

Following the choice of this well-proven scanner vehicle, the question of writing speed had to be answered. The need to accommodate a bit stream of 86 Mb/second in NTSC, or a bandwidth of approximately 43 MHz in a single head-to-tape channel, would have required a doubling of the conventional quad head-to-tape speed to a range of 3000 to 4000 ips. Such an increase was found to be undesirable for a number of reasons:

1. Centrifugal loads of the scanner would quadruple;

2. Energy exchange effects between heads and tape would become much less predictable;

3. The scanner acoustical noise would become objectionable.

The answer to the questions of writing speed lies in the ease with which parallel and serial operations can be cascaded in digital systems. With two parallel heads and recording channels, each channel can carry one-half of the bit rate, i.e., 43 Mb/second, at a writing speed that is not significantly different from existing quadruplex machines. Beyond the reliance upon well-proven scanning principles, this dual channel operation presents certain advantages with respect to error concealment and dropout compensation.

In order to accommodate two instead of one recording channel, the scanner is equipped with 8 instead of 4 heads, and thus turns into an "octoplex" system (Figure 2). Two of the 8 heads are actively reading or writing at any given time. During the write cycle, they accept their respective bit streams from a buffer memory, which in turn is fed by the input A/D converter. Before recording, identification signals and error detection bits are added to the signal. The recording code on tape is a Miller^2 type. It is one of several possible codes designed to match the lack of DC and low frequency response of magnetic recording channels.

The recording format on tape has the following parameters.

Track width:	5 mils
Guard band:	2.5 mils
Head-to-tape speed:	1600 ips
Linear tape speed:	15 ips
Linear packing density:	27Kbit/inch
Number of lines per dual head pass:	16

On playback, the two parallel head/tape channels are recovered, equalized and decoded. Skew errors between the channels and time base errors are removed with the aid of recorded identification signals. The error detection and masking systems restore the picture in areas where tape dropouts have occurred. Its performance represents a key factor in the overall subjective acceptability of the digital video picture. Single bit errors, as well as dropouts, detected by checking of the parity bit added to each video word, are masked by separate interpolation of luminance and chrominance samples from TV lines preceding and following the dropout line (Figure 3).

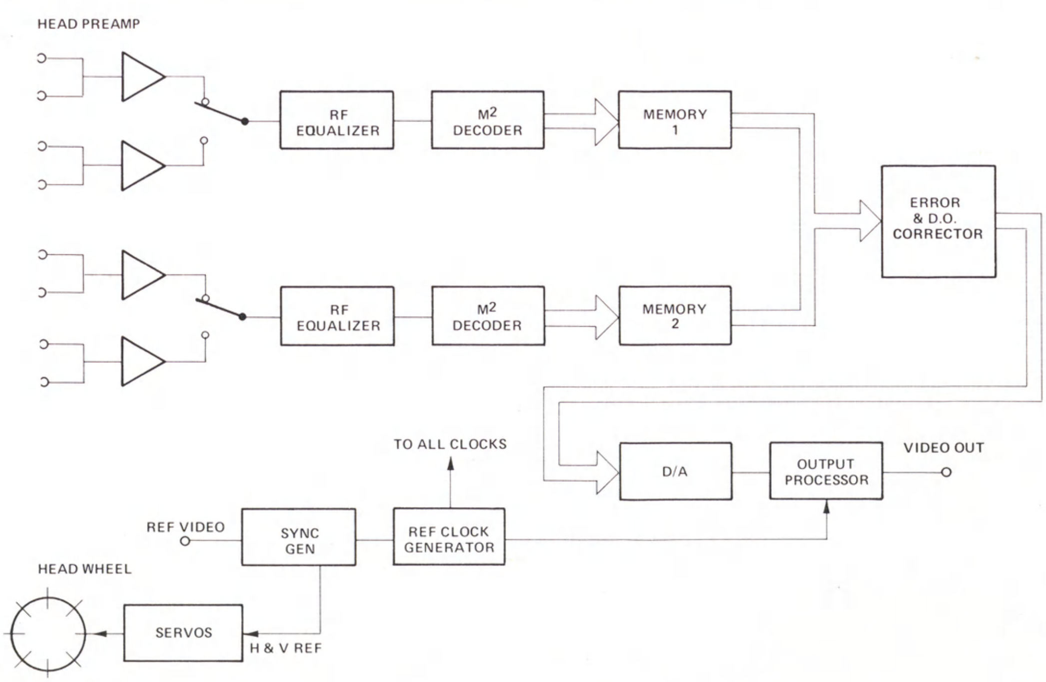

Figure 3 Digital VTR, Playback Block Diagram

AUDIO RECORDING

The performance objectives set for multigeneration video performance of a digital VTR apply equally to audio performance. Impairment with dubbing must progress slowly enough to be compatible with the video side. Error correction or concealment must be effective and able to compete with the performance of modern professional audio recorders. It has been our conviction that (a) only a digital audio channel can meet such objectives, and that (b) the audio channel or channels can make extensive use of the digital video circuits available in the machine.

This means that the audio sampling rate must be derived from a common clock with the video sampling rates in both 525 and 625 line standards. A sampling rate of 50K samples/second is convenient for this purpose. The only objection that has been raised publicly against a frequency of 50 KHz as a possible standard related to the degree of difficulty with which it can be converted to the European audio transmission frequency of 32K samples/second.

In addition to the digital audio channels using video read-write circuits, it will be useful to retain one or several lower quality analog longitudinal tracks for purposes of editing and cue messages.

Figure 4 shows the way in which digital audio is recorded on tape along with the video, providing enough space for four independent audio channels. A space of 200 mils is provided at the end of each video head swipe. The independent digital audio channels are each sampled at a rate of 50K/second and at a resolution of up to 16 bits per sample. These samples are stored in a memory that can hold them until the respective video head has reached the audio recording area and can discharge the memory onto the tape.

Each audio channel data stream is recorded twice to obtain immunity to dropout. A powerful error detection system is used to determine the validity of each sample, and correct errors when they occur.

DEMONSTRATION

(With the presentation of this paper at the conference, a playback demonstration was given with the following sequence of video signals:

Color bars
Gray field
Red color field
Transient response
Multiburst
Effect of variable record current
Four still pictures
Live camera feed
Color bars)

The intent of this demonstration is to give an impression of the video performance of the experimental VTR along with some formal measurements of its performance.

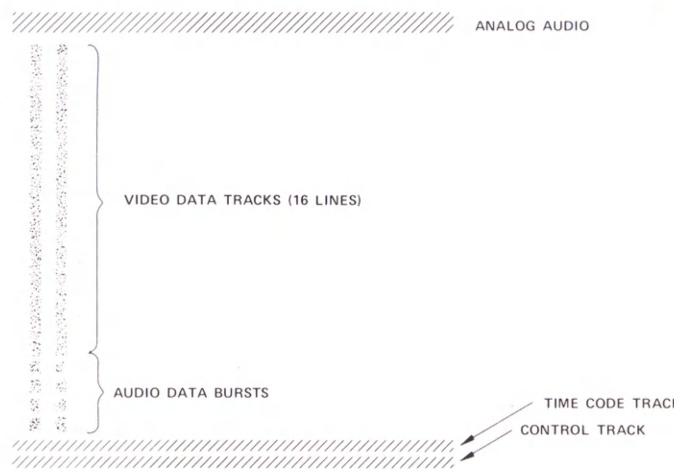

Figure 4 Digital VTR, Tape Format

OUTLOOK

The demonstration shows that digital video recording is feasible and that its quality can be outstanding. The approach taken is based on existing two-inch transverse head/tape technology. It makes no claim to have commercial significance in its present form except perhaps in some specific application areas such as post-production. Here the complete elimination of all analog picture degradations and uncertainties may rate higher than the consideration of operating costs.

It is significant, however, that the technical approach to the digital signal system involves no bit rate compromises whatsoever, and therefore implies no compromises with respect to video performance. A useful benchmark has been reached that can govern further effort. This effort must resolve the balance between lower but acceptable performance, more favorable tape consumption and a packing density on tape that can be maintained not only in the laboratory, but in a practical environment.

It must also resolve all open questions with respect to cost, operating features and diagnostic tools. A digital VTR can only compete in the marketplace if we as manufacturers continue to look for thorough solutions to our remaining problems.

Interactive computer graphics in the broadcast environment

BY H. K. REGNIER and LAWRENCE J. EVANS

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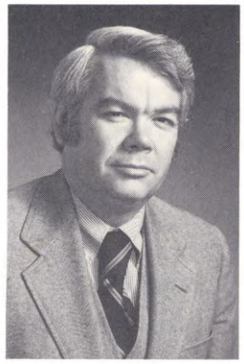
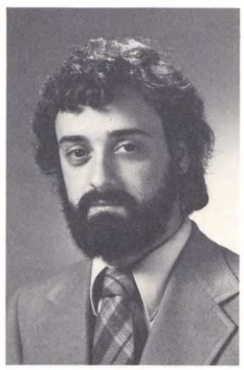


LAWRENCE J. EVANS is a staff engineer in the audio-video systems division of Ampex Corporation. Since joining the company in 1977, he has been the project engineer on the design and development of the Ampex Video Art (AVA) system. He holds a master's degree in computer science from the University of Utah.



Modern computer output devices have allowed a computer system to output data in graphics form. The most common of these devices are video displays and a variety of hard copy devices, such as plotters and film recorders. With the addition of modern input devices, such as joystick controls, light pens, and data tablets, the interactive computer graphics system is formed. Interactive graphics generally means that a human operator and the computer interact in the image generation process.

Interactive computer graphics techniques were originally developed because they presented the user with a medium that had distinct advantages over conventional graphics methods. The computer-driven display offered a more dynamic drawing and viewing area. Designing in this medium allows the user advantages, such as immediate storage and retrieval, reproducibility, size and position transformations, and faster composition.

The first and most common type of interactive graphics system has been the line drawing system. Conventionally, line drawing graphics use displays where the electron beam is directly deflected by the computer and is not restricted to a raster pattern. A list of points (any two of which define a straight line) held in a computer memory called the display file are outputted to a vector generator, which computes the necessary voltages needed to deflect the display beam. A significant advantage of this system is that the display file memory is quite small and contains data points that are easy to manipulate. These points can be held in a true three-dimensional format and displayed in perspective. Also, the line quality is sharp and smooth with a higher resolution than regular raster displays. Such systems are shown in Figure 1a.

Although these line images, especially when displayed in perspective, are very useful in some graphics applications, a logical extension of the technology was to generate half-tone and shaded (or solid) images. One popular technique uses data points to define polygons that can be filled with solid color and displayed on conventional raster displays.

However, there is another method of producing solid images on raster scan displays that is more appropriate in the broadcast environment. The use of a digital frame store memory, in place of the display file memory, allows for solid images to be formatted as a normal television picture. Instead of using data points to represent lines or polygons, the video signal is constructed from intensity samples of the generated image. Instead of a display file that consists of a list of points for screen locations, the frame memory is arranged so that it is a two-dimensional set of screen coordinates with a television aspect ratio. Each memory location in this rectangular array corresponds to a picture element (or sample) of the generated image.

A typical system is show in Figure 1b, wherein a data tablet is used as the input device. The tablet coordinates are mapped directly into frame store locations via the computer system. The frame store is also being continuously accessed in raster order to create and refresh a television display. The tablet tracks its pen position, and the system displays these positions on a television monitor at real-time video rates.

ARTISTIC APPLICATIONS

Some generalized performance requirements must be met for a computer graphics system to be practical in image generation for artistic applications. The system must function in color with operation and color selection similar to an artist's palette. The system speed in data

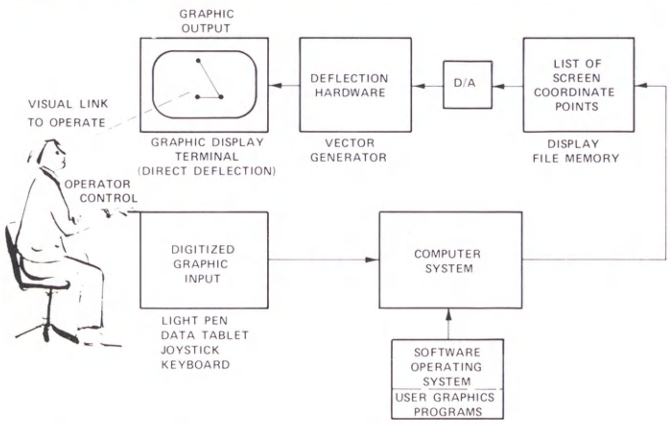


Figure 1a Line Drawing Graphics System Block Diagram

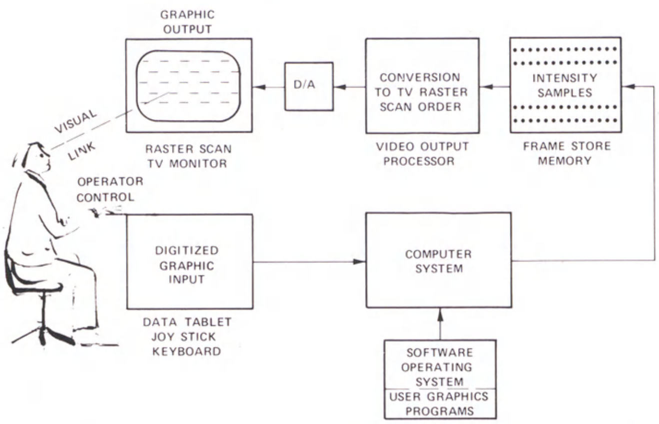


Figure 1b Raster Scan/Frame Store Graphics System Block Diagram

processing and display time must allow the artist's actions to track directly on a television display without perceivable delay. The man/machine interface must be capable of providing a natural feel to the artist with his brush and drawing pad. A system that meets this performance criteria, along with several additional features, has been assembled as an experimental model, known as the Ampex Video Art (AVA) system.

The AVA system is implemented using a general purpose time-sharing computer system. It consists of a Digital Equipment Corporation PDP-11/45 computer operating a Western Electric UNIX time-sharing software system. Its peripherals include two 80-megabyte Ampex DM-980 disk drives, two tape drives, a line printer and two terminals. Beside these standard devices, the system also includes a data tablet for digitizing pen positions and a 256K byte frame store memory with a video output processor. Figures 2a and 2b are, respectively, a block diagram and photograph of the system.

The physical configuration of the artist console consists of a data tablet, a graphic display terminal, and a standard RGB television monitor. The tablet is electrically divided into two areas, the right hand side a menu area, and the left hand side a drawing area. The drawing area corresponds to the television monitor where the generated picture will be displayed. The menu area corresponds to the graphic display terminal which displays a list of computer commands to perform system functions. As the user moves the pen over the tablet's surface, its x, y, z positions are automatically reported to the computer at 200 points per second. Note that the z position corresponds to a pressure sensitive switch in the point of the pen. Using this pen coordinate information, the computer software can determine what operation to perform.

In drawing (or painting) modes, the tablet coordinates (on the left hand side) are used to access the frame store with either drawing or cursor information. When the pen is pressed to the surface (z position = 1), the frame store is written into with drawing information in the form of color/intensity values on a picture element (pixel) basis. When pen pressure is released (z = 0), a cursor symbol is mixed with the frame store output and indicates the pen's position on the tablet.

Independent of this operation, the video output processor also accesses the frame store. The function of this processor is to read out the frame store values to the display, in raster scan order, at video rates. The speed and architecture of the MOS semiconductor frame memory is sufficient to read operations for video output and lower speed read/write requirements from the computer during operation such as picture generation, and processing.

The system menu display is a representation of all the system operating modes. It appears on the graphic display terminal and is accessed from the right hand side of the tablet. The system menu is comprised of the following commands.

Full Paint	Save Picture
Cycle Paint	Get Picture
Tint Paint	
Value Paint	Color Maker
Picture Paint	Get Colormap
Filter Paint	
	Palette
Sketch	Magnify
	Cursor
Pick Brush	History
Make Brush	
	Remove
Fill	Font
Tint Fill	Run Any Program
Full Clear	Redraw Menu
Clear Window	Exit

The left hand column of the menu shows all of the modes used in generating pictures. There are six different "painting" modes that allow the artist to create images, with free hand drawing techniques, in selectable colors

and coloring effects. A seventh drawing mode, called "sketch," gives smooth black lines of variable widths to provide a pencil sketching mode. The "brush" modes provide access to a large library of brush sizes and shapes. The ability to create new brushes and store them permanently for future use is also provided.

The "fill" modes allow the artist to fill bounded areas of the picture with any selectable color. The "clear" modes allow all or any part of the display (i.e., the frame store) to be changed to any selectable color. Both the "fill" and "clear" operations are automatic when selected. Clearing the display to a different color takes a fraction of a second to execute, and "fill" operations can be executed in fractions of a second to several seconds, depending upon the size and complexity of the filled area.

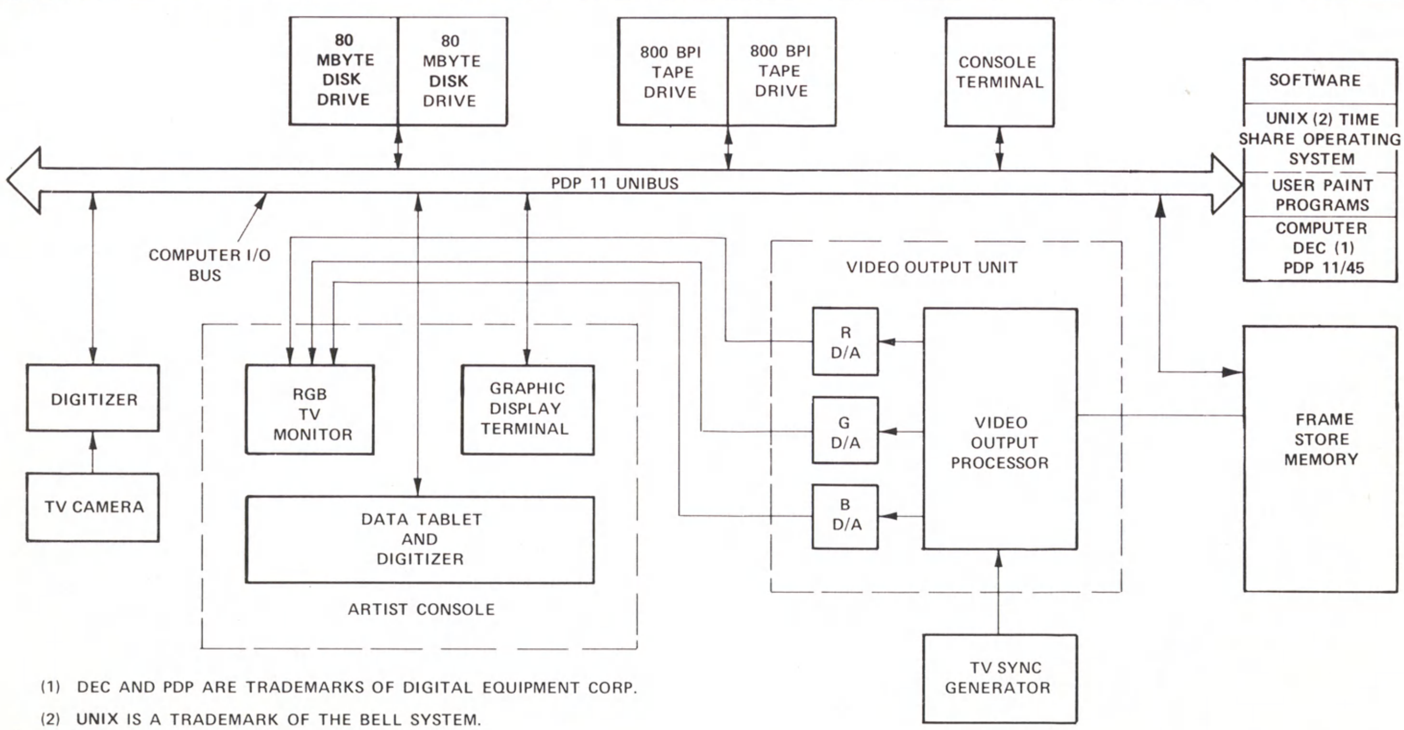
The right hand column of the menu represents various system housekeeping modes. Key among these are the "picture" modes, wherein generated pictures, or any portion of a picture, can be stored and retrieved. The "color maker" mode allows for the creation of new or modified palettes for the artist's use. The "font" mode allows for alpha-numeric characters to be added to the picture. "History" mode provides for the storage and retrieval (in a sequential non-real time playback fashion) of every color selection and pen movement made during the drawing of a picture.

The system menu can also be considered the list of user programs in the system software. Most of the programs, particularly those in the left hand column, represent complex, original programs written in a high level programming language called "C"[1,2]. ("C" language is made especially for use with the UNIX operating system.) Other programs in the list are adaptations of various features within the UNIX operating system. The user programs are stored on the system disk drives and are loaded into computer memory whenever they are selected from the tablet.

Color operation within the system is based upon a "colormap" concept. It allows a single frame store, with 8-bit resolution, to operate in the R, G, B format (the system can also operate in a hue, saturation, intensity format) without the use of three separate frame stores.

The colormap is essentially three look-up tables of digital values for R, G, B. Each table is a 256 x 12-bit memory, wherein 256 intensity combinations can be described to 12-bit resolution. When the colormap output is routed through the system R, G, B D/A converters, a "palette" of 256 unique color/intensity combinations is displayed on an RGB monitor for selection by the artist. The colormap is user-accessible from the tablet; therefore, the "palette" colors can be modified by the artist to create any desired combination of 256 colors.

Thus, the 8-bit frame store contains addresses at every pixel location that "point" to a location in the colormap look-up tables that ultimately produces the color and intensity value for each pixel in the television frame. The 8-bit frame store addresses limit the table look-ups to a total of 256 (2^8) at any one time. Figure 3 is a representation of the colormap structure. When the cursor is being displayed, its 8-bit description is inputted to the color map



(1) DEC AND PDP ARE TRADEMARKS OF DIGITAL EQUIPMENT CORP.
(2) UNIX IS A TRADEMARK OF THE BELL SYSTEM.

Figure 2a AVA System Block Diagram

in place of the 8-bit bytes from the frame store that would describe the picture content in the same location. The type of frame store and system configuration described in this section represents the AVA raster scan graphics system that is being successfully used in artistic environments.

TECHNICAL CHALLENGES

During this experimental phase of the AVA project, several artists from broadcast graphic art departments have worked on the system. Their response has been enthusiastic, and they were able to produce useful art renderings after a few hours of practice. Figures 4a and 4b are typical examples of their work. However, during this period, it was learned that certain improvements and additions were needed to more fully satisfy the broadcast application. These added requirements pose significant technical challenges in image processing technology.

Figure 2b AVA System

A common defect in digitally-generated images is the jagged edges that appear along the boundaries of an image. The effect is called "aliasing" and is a result of a lower frequency "alias" signal being generated when a high frequency signal is insufficiently sampled[3].

As an example of aliasing, refer to Figure 5 where three lines have been enlarged eight times in order to show the sampled raster structure. Note that in the camera image, a line is made smooth by blending it into the adjacent area in several steps of illumination. This blending or low pass filtering is done in a color television camera at each of the pickup tubes: red, green, and blue. In the second line of Figure 5, no filtering has been done by the graphics system, and the sharp contrasting line appears jagged. Increasing the size of the frame store memory might be considered in order to provide more samples to minimize the jaggedness. However, the single frame store should be adequate to hold a band-limited video signal according to the sampling theory (since the sampling rate is approximately 10 MHz). The real problem lies not in the frame store resolution, but in the non-band-limited infor-

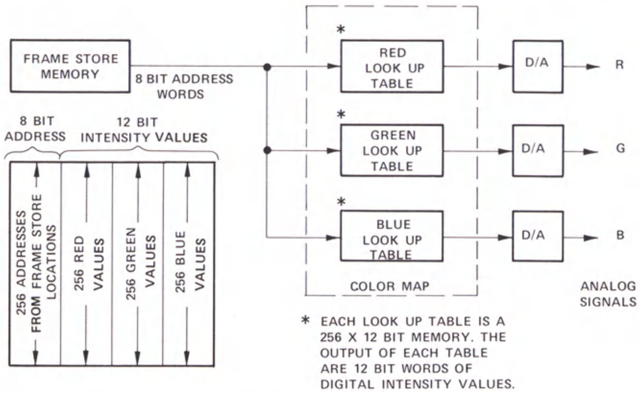


Figure 3 Colormap Structure

mation coming to the frame store from the computer-tablet combination.

The third line is an attempt to correct this situation within the computer by applying a smoothing or low pass filter function to the points before they enter the frame store memory. The results are a much smoother line that compares with the camera line quality. Moreover, objects constructed with the abrupt, jagged edges might flicker after being television system encoded due to the lack of field-to-field coherence. For example, the edges of computer-produced type fonts, which appear on one scan line but not on the next, can flicker at that edge. Thus, the need for sophisticated software filtering of the generated image is necessary prior to its loading in the frame store.

Another added requirement for the system is the ability to perform operations similar to paste-up graphics art. In this technique, picture material is gathered from numerous sources, then added to the base artwork until a suitable composite graphic is formed. This entails the use of pictures of various sizes, shapes, and colors applied to the graphic in different positions and at various angles of rotation. Lettering is also common. Thus, a computer-generated image must be capable of being compressed, expanded, rotated, and repositioned anywhere in the picture.

To accomplish these operations, linear transforms must be applied to the image. These transforms (implemented in sophisticated software routines) must preserve the detail and contour edges of the image as it is changed in size, rotation, or location. Also, effects similar to aliasing must be considered, since jagged edges of transformed images are also present. If any part of a picture is moved, rotated, or scaled, its contour edges will lie on a new background and appear jagged. This new background will have to be taken into consideration when computing the new transformed image.

As part of the paste-up operation, the system must be capable of accepting picture material from external sources such as photos, magazine clippings, and graphics cards. This can be accomplished using a television camera to acquire the picture, then digitizing its signal and entering the properly formatted digital image in the frame store. The major consideration in this operation is that the graphics system have the necessary dynamic range in R, G, B values to faithfully reconstruct the original picture as acquired by the camera.

The same dynamic range considerations are needed to accomplish effective pre-filtering to reduce aliasing and to provide good image transformation when manipulating pictures within the system. A major limitation of the colormap system is that it can provide only 256 luminance/chrominance combinations, which is insufficient for complex pictures. A major technical challenge, therefore, exists in providing sufficient range in the system while maintaining a configuration that is economically practical.

AN INTERACTIVE SYSTEM FOR BROADCASTERS

A graphics system with such features as described

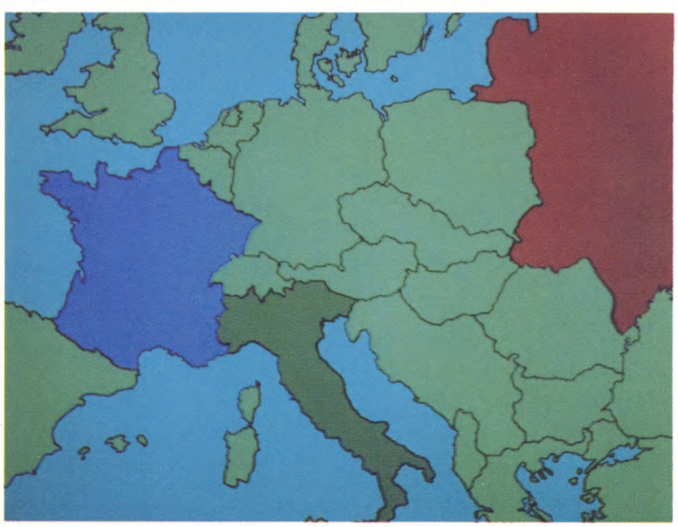


Figure 4a News Graphic from AVA System

Figure 4b Art Rendering from AVA System

in this paper offers the promise of electronic generation of all on-air graphics. When used with an Electronic Still Store™ production system, the hard copy medium is totally bypassed in both the preparation and storage of graphic material for direct on-air use (see Figure 6).

As a new art medium, the system will offer greatly increased speed and flexibility in preparing original art renderings in the paste-up techniques of graphic art. Speed and flexibility are gained by the implementation of previously described features such as:

1. Painting
   A. Instant erasure of all or any part of the picture down to the smallest detail.
   B. In a practical sense, an almost limitless selection of:
      1) Colors—in hue and intensity.
      2) Brushes—in size and shape.
      (All available to the artist in near-instantaneous time.)
   C. The ability to fill bounded areas of a picture with selected colors in times ranging from milliseconds to a few seconds.
2. Picture storage and retrieval
   A. The ability to store any part or all of a picture for future retrieval, with storage and retrieval operations taking only a few seconds.
   B. When retrieving a previously drawn picture, it can be repositioned, re-colored or augmented with additional drawing without affecting the original. It can also be repeated as many times as desired for multiple image effects.
3. Picture manipulation
   A. Hard copy material can be put into the system via a TV camera and digitizer. The picture can then be further embellished with colors, drawings, or titles.
   B. Pictures can be compressed, expanded, rotated, and re-positioned as needed.

With such features as those above, plus many other effects that can be provided by computer control of the image elements, a totally new on-the-air look can be provided that cannot be achieved by conventional art media.

Such a system should find a primary broadcast application in graphic art for news shows. Picture storage and retrieval features, as well as the "paste-up" picture manipulation capability, are key in this application.

Teleproduction usage should benefit from the original art capabilities, as well as picture manipulation and the generation of unique on-the-air effects. Picture modification capability could find usage in VTR editing applications. Scenic design is yet another production application.

Advertising and sales management could use the system for art renderings and the generation of graphs, charts, and other management visual aids.

Future broadcast applications of a computer graphics system include two particular areas of interest: animation and 3-D graphics.

For true animation, the system offers speed and ease

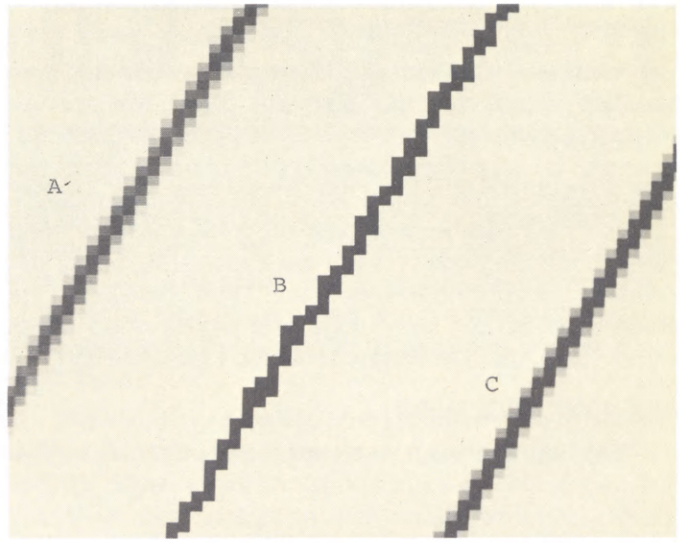


Figure 5 Enlarged Line Structure
A Digitized Camera Line
B Hand Drawn Line
C Computer Filtered Line

in drawing repetitive, closely related pictures that can be recorded on a disc or tape recorder, capable of recording individual frames (or fields), and then replayed at real time rates. Many pseudo-animation effects are also possible by such operations as manipulating the colors in a picture or by replaying a stored sequence of events that represents the picture's composition.

The type of graphics system described in this paper can generate solid, filled-in images, generally called "shaded image" graphics. In such systems, filtering can be done to "blend" or "smooth" the transitional edges of an image. Further sophistication of these filtering techniques yields shading routines, derived by mathematically modeling the light source that impart dramatic three-dimensional effects to the image surfaces. This is accom-

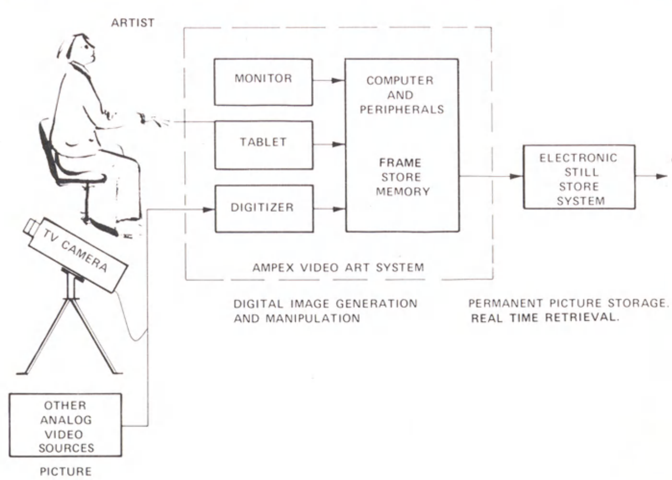


Figure 6 Source/AVA/ESS System Diagram

plished by precision graduations of the intensity and color values on the image surface[4].

Interactive computer graphics systems are made from standard, digital computer elements plus a few special-purpose peripherals. Therein lies the hope that such systems can be within the financial grasp of many broadcast organizations in the coming years. The computer industry continues to make technological progress toward offering more processing power and data storage at rapidly decreasing prices and package sizes. Thus, this step in the union of computer technology and digital video offers a promising future in image generation for television.

ACKNOWLEDGEMENT

The authors wish to acknowledge the New York Institute of Technology for their development of the original user software and the CBS Television Network for their cooperation and contributions during the feasibility study of the AVA Project.

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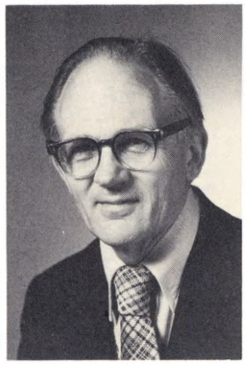
The Ampex SHBR system

BY MICHAEL O. FELIX

MICHAEL O. FELIX is the director of new product technology of Ampex Corporation. Since joining the corporation in 1960, he has worked on magnetic recorders and was responsible for the theoretical understanding of the wideband FM systems used in videotape recorders. He has been chief engineer of three Ampex divisions involving audio, video and digital tape storage. Michael received his bachelor of science degree from City and Guilds College, England.



(This paper is based on a talk given before the Tape-Head Interface Committee, November 28, 1978, in Washington, D.C. The charts and diagrams reproduced here were the graphics used in the presentation —the editors.)

The Ampex super high bit rate (SHBR) recorder operates at very high rates (up to 1 Gb/sec), at very high packing densities (over 6.6 Mbits per square inch) and has a continuously variable speed range. Its format was chosen by analyzing the fundamental characteristics of magnetic recording, and then seeking practical methods of using the resulting conclusions.

Figure 1a shows a reference system in which a single bit has been recorded across a track on a piece of magnetic tape. If it is planned to double the packing density (measured in bits per square inch) this may be done in two ways; either the track width can be halved (Figure 1b), or the wavelength may be halved (Figure 1c), in which case the BPI is doubled.

The output from magnetic tape fundamentally consists of two components: a signal formed by the voltage addition of all the more-or-less identical particles more-or-less lined up in a particular direction, and a noise formed by the addition of the random components since the particles are neither precisely the same nor precisely aligned; these noise components add powerwise because they are the sum of random components in random directions.

When the track width is halved, the number of magnetic particles per recorded bit is also halved. Thus, the signal voltage is halved (a loss of 6dB) and the tape noise power is also halved (a loss of 3dB). Depending on whether the system is limited by tape noise or by other sources (head and preamplifier noise, for example), the SNR will drop between 3 and 6dB. If on the other hand, the wavelength is halved, then not only is the length along the track halved, but the depth of recording into the tape is also halved*. The number of magnetic particles per bit therefore is reduced 4:1, with a 12dB loss of signal and a 6dB reduction of tape noise. Thus the SNR decreases a minimum of 6dB. The upper limit is in fact considerably over 12dB, since the shorter wave lengths make the system more sensitive to head-to-tape spacings and to other head losses.

High packing densities force the use of narrow track widths, a fact well recognized in the video and disc recording industries as shown in Figure 2. This shows the history of track widths on deliverable machines. Today mass produced consumer video recorders use track widths of less than 2 mils, and computer disk systems use track widths of less than 1 mil. The instrumentation industry has not followed a parallel path because of the strength of the IRIG formats, which are excellent for their original analog purpose but are unsuitable when high digital packing densities are essential.

Figure 3 shows the gain to be made from using narrow tracks. The upper chart plots BPI versus tracks per inch (TPI) to achieve 30dB SNR on 300 Oe tape. The 30dB was chosen so that a 12dB drop-out just drives the system to its threshold where digital errors increase precipitously.

*This assumes the wavelength is less than the tape thickness, a safe assumption in high bit rate systems.

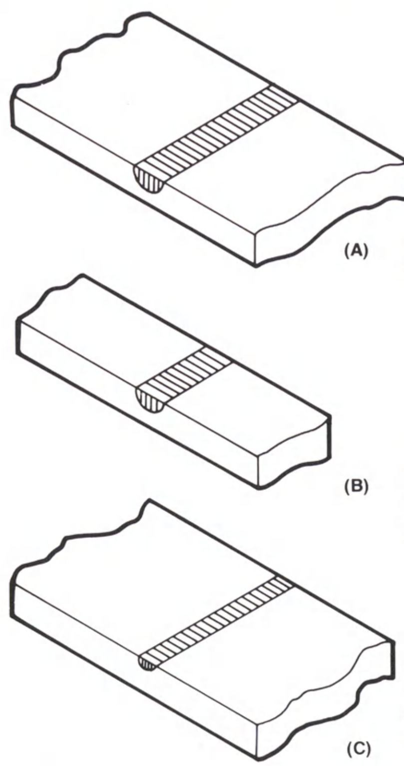


Figure 1 Half Trackwidth v Half Wavelength

This corresponds on today's quality of tape to between 1 in 10^6 and 1 in 10^7 bit error rate (BER).

The upper chart in Figure 3 shows that at 28 TPI, around 30,000 BPI may be recorded, corresponding to a common standard in today's industry. At 670 TPI (the TPI for SHBR), the bits per inch drop to 10,000. The lower chart shows the resulting packing density. The 28 track system is below 1Mbit per square inch; the SHBR is close to 7 Mbits per square inch.

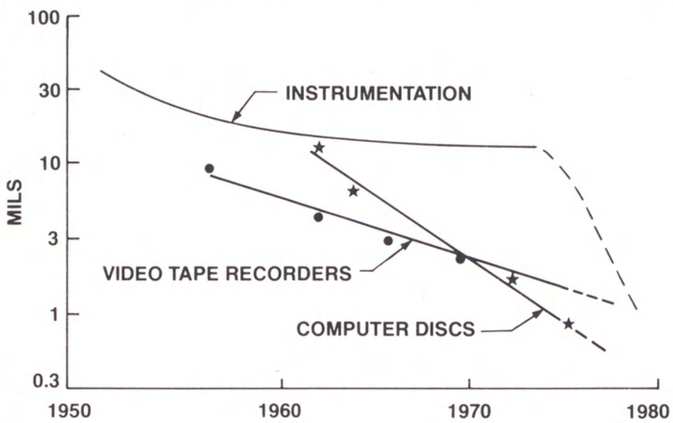


Figure 2 Trackwidths

TYPES OF RECORDER

In the SHBR design three types of recorders (Figure 4) are considered: longitudinal in which a tape is pulled past a multi-track stationary head; helical in which a tape is wrapped in a helix around a rapidly rotating disc containing a pair of head stacks (this is typical of today's video recorders); lastly, a transverse format in which the tape is formed into a "canoe" and a rapidly rotating head-drum writes tracks across the tape.

The latter system, typical of early video recorders, was eliminated because of head wear problems, leaving the choice between longitudinal and helical.

The helical recorder decouples track width from the number of heads. If one has a system running with 5 mil tracks, and wishes to change to 2.5 mil, one need only change the head width, and halve the tape speed, keeping the drum rotation fixed.

In the longitudinal recorder, in contrast, half the track width means twice as many tracks, heads, electronics, and adjustments. Any further increase over today's standards is an unattractive solution to tomorrow's problems.

VARIABLE DATA RATES

All digital systems require at least multiple data rates; a continuously variable rate which can be slaved to an external clock would greatly simplify many systems.

In longitudinal recorders two approaches are possible. Using continuous tape motion, multiple tape speeds are provided; however, since every speed change produces a frequency change, there must be a record equalizer, playback equalizer and low pass filter for every speed and every track. Even for the wide tracks used with 28 track systems, and with seven speeds this multiplies up to 196 sets of components and their corresponding adjustments. The comparison on faster data rates is given in Paragraph 7 later in this paper.

An alternative method is to use intermittent motion where the tape moves in bursts, but always at the same

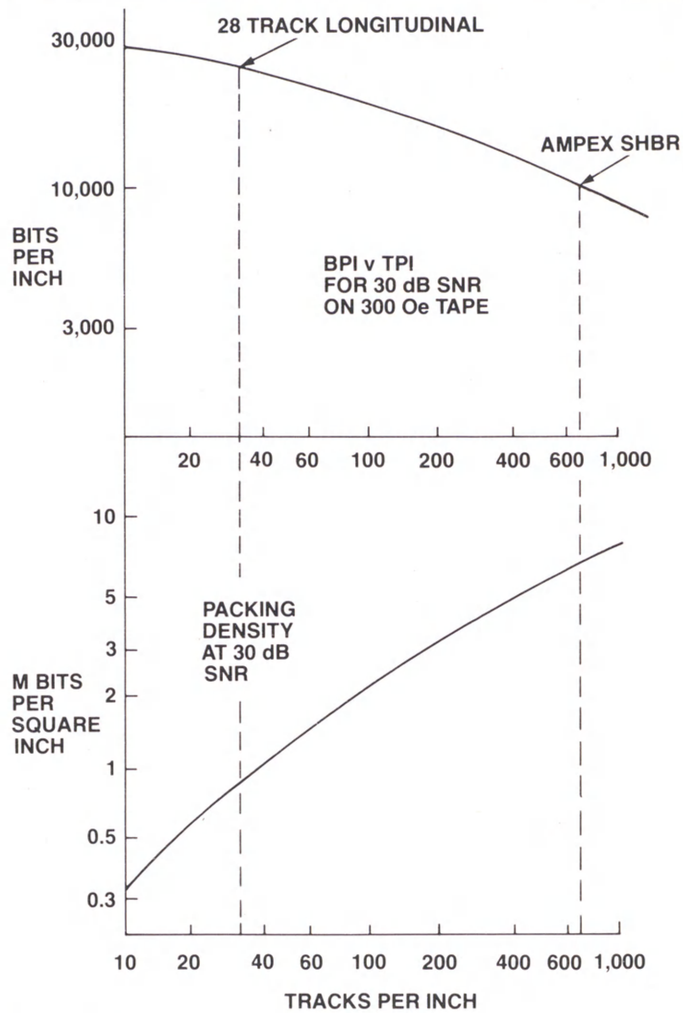


Figure 3

speed. Speed changing is then performed by filling a buffer at a fast rate, and emptying it at the user rate. This greatly simplifies the electronics by eliminating the speed adjustments. On the other hand, it subjects a format which is extremely sensitive to head-to-tape separation to a "jerky" tape motion.

The helical solution is very much more attractive. It is in essence "intermittent" since data is written in "swipes" across the tape. Variable data rates are derived as shown in Figure 5.

Consider a system in which the tape is stationary but the drum is rotating normally. The head will then follow a

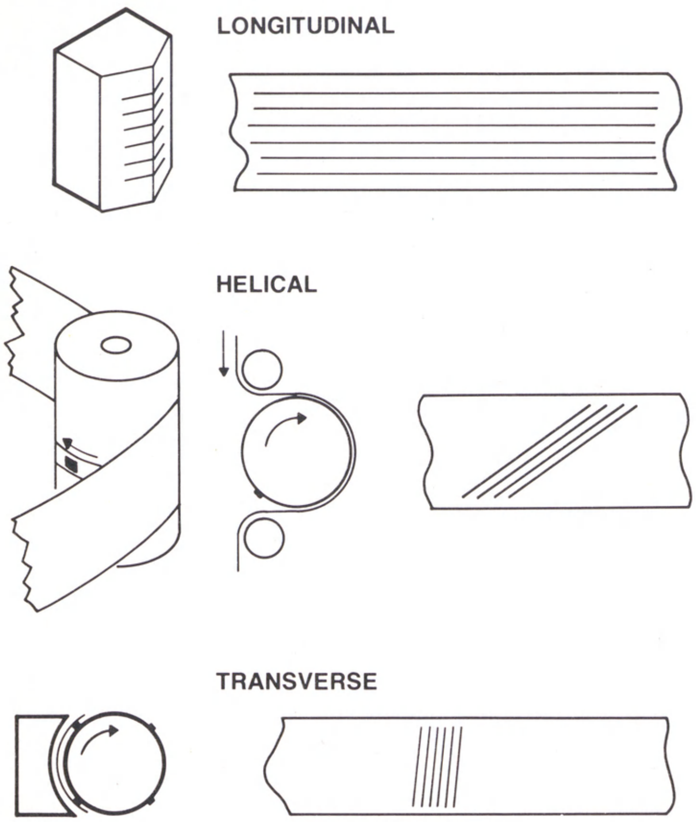


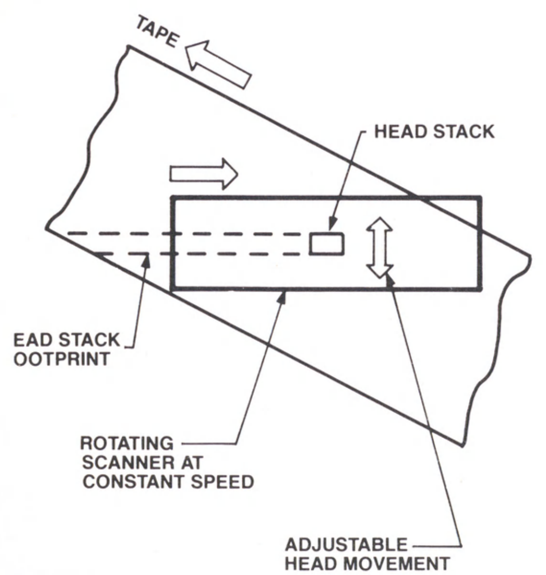
Figure 4 Types of Recorders

path shown dotted in Figure 5b. Now move the tape; by the time the head has moved from A to B, the tape will have moved from C to B, so the head now writes a track A-C on the tape.

Ampex has developed an AST automatic scan tracking (AST)™ system in which the head is mounted on an arm that can move at right angles to the track (Figure 5a). If the tape is written at normal tape speeds, and the tape is then stopped (but with the drum speed unchanged), the tape track will be A-C (Figure 5b) but the uncorrected head path will be A-B, i.e., the head starts reading one track and exactly cross-tracks to the adjacent one.

By applying a linear saw-tooth to the AST mechanism (Figure 6c), the head may be kept precisely on track. The head now reads the track repetitively; on any pass a buffer may be loaded (Figure 6e) with the data in one head "swipe"—about 1.3 Mbits. The buffer is unloaded at the slow user rate. The diagrams in Figure 5a and 5b are grossly exaggerated to make the effects clear. The track lengths in reality are 5 inches, the track spacing 45 mils. Thus azimuth changes for example are negligible, and not alarming as they appear in the figure.

The proposed helical format wraps the tape 180° around the drum (Figure 4); there are two sets of heads, each of which read or write for half the time. Therefore, following the linear saw-tooth of Figure 6c, there is an

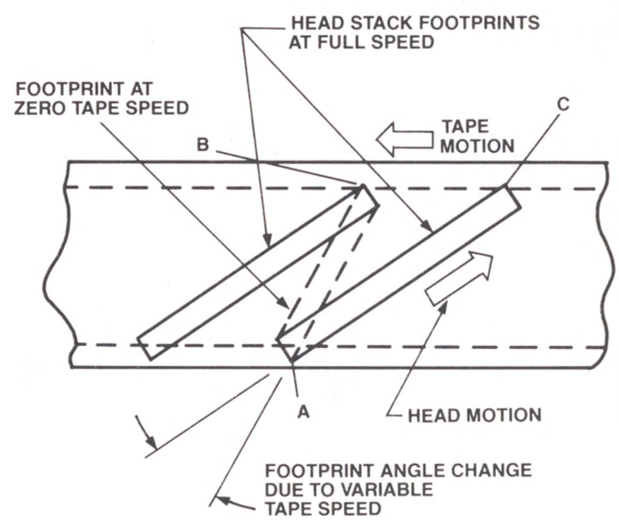


SCANNER TO TAPE GEOMETRY

(a)

CONSTANT PACKING DENSITY IS MAINTAINED AND TAPE SPEED IS VARIED TO ACCOMMODATE VARIABLE DATA RATES. THIS CHANGES HEAD STACK FOOTPRINT ANGLE ON TAPE. ANGLE ADJUSTMENT IS PROVIDED AUTOMATICALLY BY AST.

AST ASSURES PROPER TRACKING EVEN ON DISTORTED TAPE.



HEAD STACK FOOTPRINTS

(b)

THE AUTOMATIC SCAN TRACKING IN CONJUNCTION WITH THE USE OF DIGITAL BUFFER ALLOWS VARIABLE DATA RATES AT CONSTANT PACKING DENSITY ON TAPE.

Figure 5 Automatic Scan Tracking

equal time for the AST mechanism to return to its starting point; this return need not be linear.

In Figure 6d, the AST waveform is shown for reading or writing at one third full speed. In this case the heads read each recorded track three times and then jump to the adjacent one. The AST motion comprises two super-imposed saw-tooth waveforms, the first is the "once-around" saw-tooth, the second proportioned to the three times slow down. Speed changes need not be in integral numbers. For example if nine tracks are read three times and each tenth track is read four times, a reduction of 3.1:1 ensues. Extending this principle, a continuously variable data rate can be provided.

The auto tracking information comes from two sources. A microprocessor controlled system calculates the theoretically required waveform, which is itself generated in hard wired logic. In addition the di-bit pattern standard in the computer disk world is recorded, and this closes a second slower speed tracking loop. This latter loop corrects for all minor defects whether tape originated (e.g., humidity caused dimensional changes) or machine originated (e.g., minor differences between machines).

Since the machines can operate with the tape stationary (and the drum spinning), the machine can be cued, and the buffer filled with a 1.3 Mbit "swipe" before the "Start Data" command. This data is therefore available immediately; the maximum data rate occurs when there is just time to reload the buffer from the next "swipe" before the buffer is emptied.

The first designs are not optimizing this factor and will operate up to 100 Mbits/sec. Experiments have started to improve the data rate at which instantaneous starting is possible.

THE AMPEX FORMAT

The selected format (Table I) is a hybrid between the longitudinal multi-head, and the conventional single head helical approaches. It uses two 27 heads-per-stack in a 180° helical format. This format is particularly suitable for an automatically loaded cassette system, as is found throughout the line of industrial video tape recorders. The track width is 1 mil, and the track spacing 0.5 mil. The whole 27 heads, plus two servo di-bit tracks, is 45 mil wide, which is about equal to a single track-width on a 14 channel longitudinal machine. These very narrow tracks are startling to many longitudinal recorder users. However, helical machines with comparable track widths such as the Betamax™ and VHS™ systems are built in large numbers and operate reliably in the often hostile consumer environment!

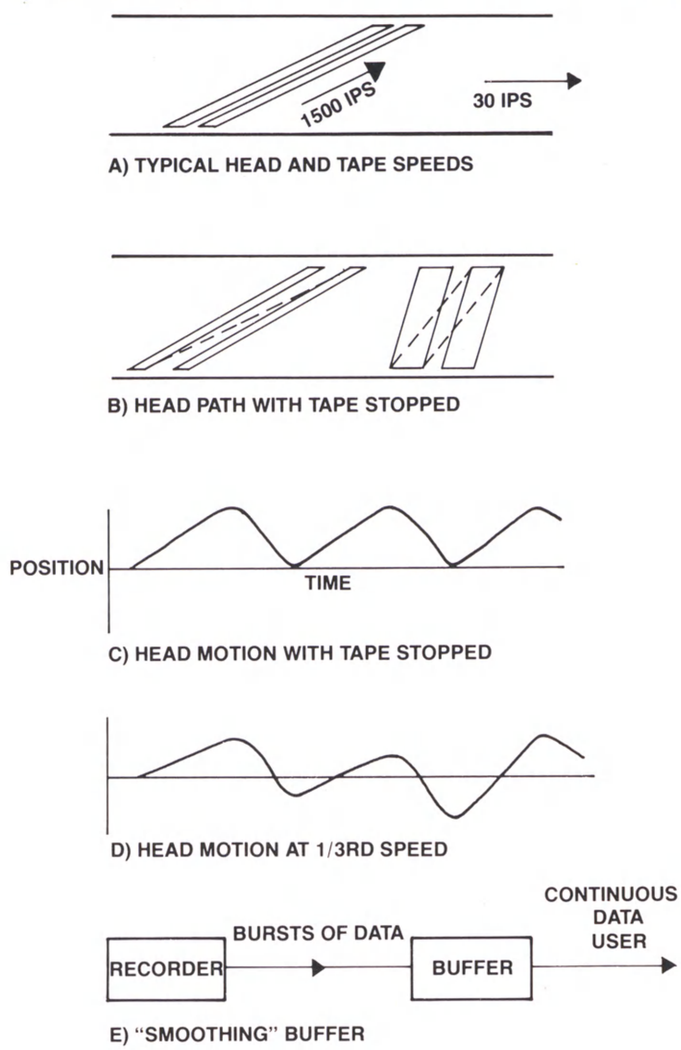


Figure 6 Variable Data Rates in Helical Recorders

- 180° HELICAL WRAP WITH 5″ DIA SCANNER.
- 2″ TAPE WITH PRESENT OXIDE CHARACTERISTICS.
- 2 SETS OF 27 TRACK HEADS, EACH WRITING UP TO 37 Mb/SEC. AT 10 Kb/IN PACKING DENSITY PER TRACK.
- HEADS WITH 1 MIL TRACKS ON 1.5 MIL CENTERS.
- 15 MICROINCH AIR SEPARATION BETWEEN TAPE AND HEAD.
- CONTINUOUS AUTO SCAN TRACKING.
- SPEED CHANGING VIA DIGITAL BUFFER, GIVING CONTINUOUSLY VARIABLE INPUT/OUTPUT SPEEDS.
- FIXED EQUALIZATION AS IN TODAY'S COMPUTER DISC RECORDERS.
- "INSTANTANEOUS" START/STOP CAPABILITY.

Table I The Ampex Selected Format

In contrast to the tracks per inch, the bits per inch are very low—only 10,000 corresponding to a 200 micro inch recorded wave length. The system is thus relatively insensitive to head-to-tape spacing (0.27 dB per microinch), and to tape surface defects. In addition, this has let us "fly" the tape over the heads. The aerodynamics are carefully controlled to keep a 15 microinch air separation. This reduces both tape signal and tape noise by 4 dB; the SNR loss is less than 1 dB since other sources of noise are small. This air separation is an essential part of the variable speed system; with the tape stopped, the head traverses the same track 300 times per second. Experiments have been run for many hours under these

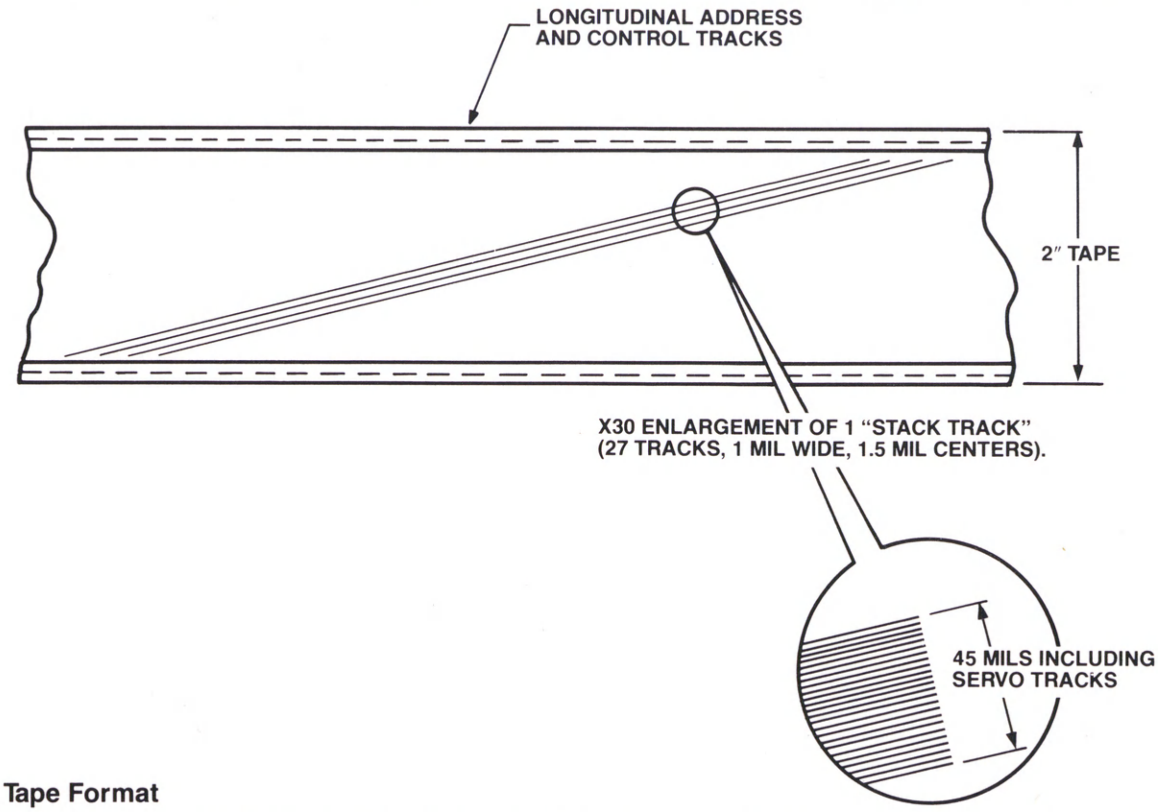


Figure 7 Tape Format

conditions showing no evidence of the 15 microinch flying height. In a more direct measurement, light has been pulsed through transparent, uncoated tape, having the same physical characteristics as the final tape. Reflection off the head then produces the well-known interference color bands; not only does this show the absolute separation but it shows the uniformity over the whole head area under dynamic conditions.

Another advantage of the low BPI is that equalization in both record and playback is simplified. Our aim is to have no adjustments, but in our forecasts we have allowed for one adjustment in each of the 27 channels. As a comparison, computer disk systems record at close to 7000 BPI on tracks less than 1 mil wide, and switch one adjustment-free record/playback system to any of nineteen heads.

The tape format is shown drawn to scale in Figure 7. Each "swipe" is 45 mils wide and includes both the 27 data channels and the two servo channels. These tracks take 1.6 inch of the 2 inch tape width, so that sensitive, narrow track information is not laid down near the trouble-prone tape edges. Several longitudinal, low density tracks are written, including an address track. This lets one identify and search for any "swipe" in a 15″ reel of tape holding over 1 Tbit (10^{12} bits) of information.

The gross packing density is 10,000 BPI and 670 TPI, giving 6.7 Mbits per square inch. Allowing for the 1.6 inch swipe width and 8 percent synchronizing overhead re-

(ASSUMING 5 MB/SQ/IN USER PACKING DENSITY)

BIT RATE MB/s	RECORD TIME MIN	TAPE LENGTH FEET	REEL DIA INCHES	TOTAL STORAGE BITS
1000	21.6	10800	15	1.30×10^{12}
600	30.6	9200	14	1.10×10^{12}
300	72.0	10800	15	1.30×10^{12}
200	92.0	9200	14	1.10×10^{12}
100	184.0	9200	14	1.10×10^{12}
20	1080.0	10800	15	1.30×10^{12}

Table II Examples of Storage Capacity User Data

duces the net user density to 5Mbits per square inch. Table II then lists some possible combination. These assume 1 mil tape thickness with the magnetic characteristics in use today in helical videotape recorders. The use of thinner tape which would reduce the reel size may be possible but is not presently planned. Splice-free lengths over 10,800 feet are not generally available.

In the first embodiment, each of the 27 heads will read or write 30 Mbits/sec. The total rate on tape is therefore 810 Mbits/sec. Subtracting the 8 percent overhead results in a user rate of 750 Mbits/sec. However, the design is such that later increases to over 1 Gb/sec appear practical; improved tapes will let the BPI increase and the mechanics have been conservatively designed to operate with good safety factors at the present rates.

	LONGIT.	180°C HELICAL
• NUMBER OF PARALLEL TRACKS	160	27
• HEADS/TRACK	1	2
• TOTAL NUMBER OF HEADS	160	54
• K BITS/INCH/TRACK	42	10
• TAPE SPEED, IPS	150	90
• ADJUSTMENTS/TRACK/SPEED	3	1
• ADJUSTMENTS FOR 7 SPEEDS	3360	27
• HEAD WEAR	LOW	LOW
• NEEDS SPEED BUFFER?	NO	YES
• CONTINUOUSLY VARIABLE DATA RATE	NO	YES
• STORAGE ON 10,000 FT.	8×10^{11}	1.25×10^{12}

Table III Comparison of 1 Gb Sec Approaches Using 2″ Tape

LONGITUDINAL AND HELICAL APPROACHES

Table III shows a comparison of the longitudinal and helical approaches to a 1 Gb/sec recorder. The longitudinal system must use a large number (160) of relatively wide tracks (8 mils) and so must use an uncomfortably short wavelength (48 micro-inches corresponding to 42,000 BPI). Even then its packing density is nearly 40 percent lower. However, it is in the complexity (and cost) of the electronics that the comparison is most dramatic. At 42 KBI, three adjustments per speed per track are considered a hard figure to meet. The total adjustments are then 3360. Contrast the no-adjustment design goal and the 27 conservatively allowed in the helical approach.

ACCOMPLISHMENTS

With an approach so dramatically different, Ampex decided to run a feasibility program before committing to a full scale design. This program is near completion and had the following aims:

1. To demonstrate reading and writing 1 mil tracks on today's tapes with BER of better than 1 in 10^6 —complete.
2. To design an aerodynamic system which would fly tape 15 ± 2 microinches over the full surface of a 27 track head—complete.
3. To design an AST system which would jump over 40 mils in 3.3 milliseconds, including settling to better than 0.2 mils—complete.
4. To calculate the theoretical crosstalk performance of such a system and to show it was over 30 dB down on the wanted signal—complete.
5. To assemble a system with multitrack heads, and demonstrate BER, crosstalk and AST performance—partially complete.

In addition the design of prototype units, both ground and airborne have now started, since the probability of success is very high.

RECORDING CODES

The SHBR system, like all Ampex high density digital systems, uses Miller². This has the advantages of no increase in transition density over NRZ, no DC component, and little low-frequency energy. Its one disadvantage is the double clocking rate.

Miller codes are widely used. For example, disk recorders using 800 tracks per inch with gross packing densities of 5 Mbits per square inch achieve BER's of 1 in 10^{10}. Miller² is used in Ampex's digital video disc recorders, which have proved to be ideal systems for detecting pattern sensitivity. Miller² is the only code found totally free of it.

CONCLUSIONS

In any magnetic system, a high packing density forces the use of the narrowest possible track width.

Narrow tracks can only be efficiently handled in rotary head recorders which decouple track width from the number of heads and sets of electronics.

Helical systems can provide the tape flying and auto-tracking systems which permit continuously variable user data rates without adding any adjustments to the read/write systems. The long recorded wavelengths and the tape flying together results in much less sensitivity to tape surface quality. The auto-tracking system not only provides variable speed operation but also compensates for temperature and humidity changes in tape, and for interchange differences between recorders.

Systems with gross packing densities of 6.7 Mbits per square inch are already running. Future improvements in tapes and heads should let this increase to at least 15 Mbits per square inch. User data rates are presently at 750 Mbits/second, and will increase to over 1 Gbit/sec.

Towards 1000 megabit-per-second magnetic recording

BY JOHN C. MALLINSON

JOHN C. MALLINSON is the manager of the magnetic recording technology department in the advanced technology division of Ampex Corporation. He has conducted work in magnetic recording theory, high density head fabrication, coding and communications theory, and the exploration of advanced concepts in various areas of recording. A native of England, he joined Ampex in 1962 and holds a master's degree from University College, Oxford.

Current high bit rate (HBR) recorders are based upon minimal modifications of longitudinal multi-track instrumentation recorders. Typically 28 or 42 tracks per inch (TPI) are used at 30,000 bits per inch (BPI), yielding areal bit densities of approximately 10^6 bits per square inch. At 120 inch per second (IPS) tape speeds, data rates close to 100 Mbs per inch of trackwidth are thus attained.

While modest increases in areal density may be anticipated with further development of longitudinal recorders, it appears that they will be incapable of meeting forthcoming digital recording requirements in the fields of satellite imagery and digital processing of analog signals. There are several current requirements in the range 500-750 Mbs with planned increases to 1000 Mbs expected within five years.

In 1976, the problems of recording such high rate data were studied anew, with the conclusion that a new tape format and machine configuration would be required for data rates above 300 Mbs.

In this paper, the design philosophy followed in designing the new system is reviewed. This material has already been covered in a previous paper in greater detail[1]. Thereafter, recent achievements in miniature multichannel head technology, automatic scan tracking and digital bit error rates are discussed.

DESIGN PHILOSOPHY

Previous experience in digital audio and video, computer tape and disc recorders indicated that a nominal 30 dB SNR is necessary for bit error rates (BER) better than 10^6. According to the physics of magnetic recording, the (power) SNR is proportional to the trackwidth and inversely proportional to the square of the BPI.[2] For a given SNR, it follows that greater areal density is attained with a multiplicity of narrow tracks each recording data at relatively low linear densities. Approximately, the areal density increases as $\sqrt{\text{TPI}}$.

In order to design a recorder with the eventual potential of accepting 1000 Mbs with reasonable tape widths (2 inches) and speeds (<150 IPS), an areal density close to 4 x 10^6 bits per square inch net is needed. This areal density compares closely with those achieved in current computer disk file commercial practice (IBM 3344, 3.2 x 10^6 gross; Ampex DM-9160, 4.8 x 10^6 gross). Accordingly, a similar format (1 mil track-width, 667 TPI, 10,000 BPI) yielding 6.67 x 10^6 bits per square inch gross was selected. This allows for the addition of a substantial quantity of "housekeeping" data (synchronization words, block and frame identification words, etc.).

A longitudinal machine is clearly out of the question with 667 TPI due to inordinately high number (1334) of heads and electronic signal channels needed. A rotary head machine, in which the TPI and the number of heads may be selected independently, is required.

A 180° scan helical configuration was selected for a number of reasons. The low and uniform head-to-tape pressure facilitates the design of "flying" heads where a deliberate, controlled head to tape spacing (15-20 microinches) is produced aerodynamically as in the IBM 3850.[3] Further, the design of tape auto-threading and cassette mechanisms is relatively simple as witnessed by the proliferation of Japanese ½ inch helical consumer video tape recorders (VTRs).[4]

In current broadcast helical VTRs, head to tape relative speeds of 1000-1500 IPS are employed with electrical bandwidths up to 20-25 MHz. Operation at 3000 IPS was selected for the new machine which, at 10,000 BPI, gives data rates of 30 Mbs per channel, a rate well within the frequency limitations of current video heads and circuitry. Thus, in order to record 1000 Mbs, some 30-40 channels must be employed simultaneously.

It was decided that the best way to achieve this was to construct miniature multi-track head stacks. Two types have been produced; the first is based upon multiple saw-

ing operations into a monolithic ferrite block and has already been described. The second type, thin film inductive heads produced by deposition, photo-lithography and etching techniques, will be emphasized in this paper.

The utility of such a super high bit rate (SHBR) recorder is greatly enhanced if provision can be made for it to record and playback data at other than the maximum rate. In conventional longitudinal HBRs, this data rate changing is accomplished by the sole expedient of slowing down the tape speed. This technique, though simple, is expensive and limited to pre-determined data rates and tape speeds because a different set of electrical filter networks is required for each rate and speed.

Rotary headed machines are, on the other hand, inherently "bursty" data recorders. The data bursts correspond to the passage of the head-stack across the tape. If the rotational rate of the head wheel or drum is held fixed, the data is handled in bursts at a constant data rate. By storing these bursts in a suitable buffer memory, the input or output data rates of the machine may be made totally flexible. With the constant reduction in the prices of semi-conductor memory, the trade-off between digital buffers and analog filters becomes increasingly favorable to buffers. At reduced data rates, the speed at which the tape passes through the recorder must, of necessity, be reduced proportionally. Because the actual head trajectory across the tape has two vector components—the peripheral speed of the head drum and the tape speed—it follows that changing tape speeds is accompanied by changing trajectories as shown in Figure 1. In order to compensate for this, the SHBR incorporates an automatic scan tracking system (AST), which is, in principle, analogous to that used in the Ampex VPR series of broadcast VTRs.[5] Some details of the modes of operation and performance of the AST system will be given.

At data rates below the maximum, it follows that individual trajectories may be scanned repeatedly by the head stack. It was decided that this multiple scanning characteristic of the SHBR made it mandatory that there be no actual contact between the head and the tape. Accordingly, the complete multi-track head stack is mounted in a specially contoured and slotted slider. This self-acting aerodynamic bearing causes the tape to "fly" some 15-20 microinches above the head and, consequently, indefinitely long duration "still-framing" is possible. The spacing is measured by white light stroboscopic interferometry (Newton's colors).

At the chosen low lineary density (10,000 BPI), this spacing reduces the playback signal by about 4 dB, but since the tape noise is reduced equally, the overall SNR is degraded by about 1 dB only.

Not withstanding the inherent capability of the AST to correct tracking errors (due to interchange, etc.), it was decided to ensure extremely accurate tape guidance by using the so-called natural topology together with air lubrication throughout the tape path. In the natural topology,

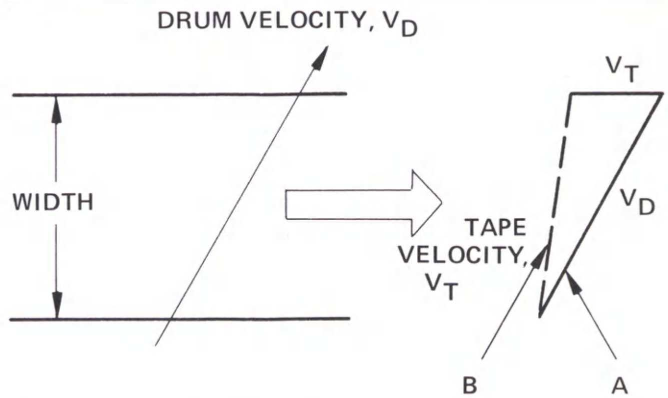


Figure 1 Velocity Triangles Showing the Head Trajectory for A) Stopped Tape and B) Moving Tape

the tape suffers simple bending only without twisting. The principal virtue of this arrangement is that only very small (ideally zero) edge guiding forces are required. All static parts of the tape path are provided with externally pressurized bearings; the rotating drum and heads are self-acting as described already. From reel to reel, nothing touches the oxide side of the tape; the reverse side touches only the walls of the tape tension controlling vacuum chamber.

The following table summarizes the principal tape and machine format parameters selected for the interim 750 Mbs machines:

Tape Type:	current production video tape
Tape Width:	2 inch standard
Tape Length:	10,000 feet maximum
Track Width:	10^3 inch
Guardband Width:	0.5 10^3 inch
Track Density:	667 per inch
Linear Density:	10,000 bits per inch
Channel Code:	$(\text{Miller})^2$
Areal Density:	6.67 10^6 bits per square inch
Tape Speed:	50-100 inch per second
Machine Type:	180° wrap helical rotary
Number of Head Stacks:	Two
Number of Tracks:	25-30 tracks per head stack
Head-Tape Speed:	3000 inch per second
Head-Tape Spacing:	15 microinches

THIN FILM HEADS

It was decided that two independent approaches to the difficult task of producing multi-track head stacks would be followed. In the first, which has been described previously, mono-lithic gapped blocks of manganese-zinc ferrite were saw-cut, glass-filled, provided with seven turn pre-formed coils, and bonded. This technique produced the first working head stacks with the BER results discussed below.

The second, parallel effort was to fabricate single turn inductive thin film heads. It was decided to make

these heads in assemblies of 15 tracks each as shown in Figure 2. Visible are the low inductance deposited strip lines radiating out from the 1 mil track-width pole-tips which are placed upon 3 mil centers. The gaps in the strip lines are provided for the subsequent installation of seven-to-one turn ratio impedance matching transformers. Outboard of the transformers, the signal levels and impedances closely approximate those found in the multi-turn ferrite heads described above and those used in conventional VTRs. In Figure 3, several pole-tips are shown at higher magnification. It will be noted that photo-lithographic resolution is comparable to that employed in the semiconductor industry.

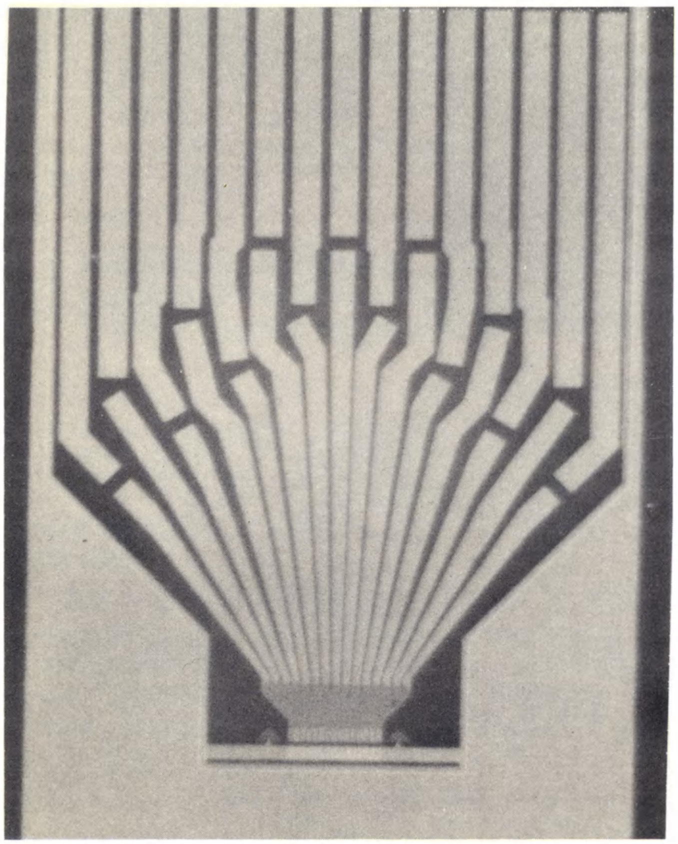


Figure 2 Fifteen Channel Thin Film Head Assembly

As has been explained previously, a worthwhile improvement in the output spectrum of thin film heads can be obtained by proportioning the pole-tip to gap-length ratio so that the "low" frequency head bumps offset the normal gap-loss effort.[6] We have observed gains exceeding 4 dB due to this effect. Eventually, it is planned to utilize two of these 3 mil center to center thin film head assemblies "interlaced" to form a head stack with 30 tracks on 1½ mil centers.

AUTOMATIC SCAN TRACKING (AST)

The behavior of the AST system can best be appreciated by considering an example. Suppose the average data rate is one fifth the maximum. It follows that there need only be one active (i.e., writing or reading) scan followed by four idle scans (note that in current variable rate broadcast VTRs, no buffer is used and in this case all scans must be active).

There are two separate modes of AST operation necessary. First, since the tape velocity is only one fifth of the maximum, the head stack must be moved during the scans in order to follow the correct trajectory (see Figure 1). This mode is controlled by a wide-bandwidth servo loop whose error signal is proportional to the difference between the position of the head relative to the drum and the required head position, as computed from the knowledge of the actual tape speed.

Second, in order to ensure that the heads track accurately pre-recorded data, a relatively low bandwidth servo loop is established using off-tape error signals derived from specially recorded servo tracks. This mode is, of course, able to compensate for track position errors due to interchange, temperature, humidity or other factors.

Both modes act upon a single head stack actuator which moves the stack parallel to the drum rotational axis over a strike rather in excess of the total head stack width. The actuator is, of course, subjected to an extremely large radial centrifugal field which, for a given scanning speed, is inversely proportional to the drum diameter. This factor is one of the principal mechanical constraints in SHBR design. Drums with diameters in the range 3-6 inches are under consideration.

In recent testing, it has been shown that it is possible to make full head stack width ($\approx$40 mil) jumps in less than 180° rotation of the drum. After such a jump, it is critical that the head stack "lands" at exactly the correct position and is traveling in the correct direction so that the next set of tracks can be read correctly on the next swipe. In a recent demonstration, the tracking error on the swipe immediately after the jump was nowhere greater than 10 μinches. With 1 mil trackwidths it follows that the loss in SNR due to mistracking is only about 1 dB and only a small change in BER is incurred.

BIT ERROR RATES

After a careful study of channel (or modulation) codes, it was decided that the recently described dc free varient of Miller (MFM or delta-modulation) code termed Miller^2 would be used.[7] Since transmission of dc through a magnetic recorder is not possible, the presence of dc in a channel code invariably leads to output waveform distortions such as "base line wander." Miller^2 was chosen because it requires very little memory (2 bits) to implement and, having transitions no closer than one bit cell, requires very little more bandwidth than NRZ.

The channel equalization problem was treated carefully. Since the overall channel is of necessity extremely non-linear, the channel equalization must be split correctly into pre- and post-equalization components.[8] The

proper pre-equalization causes the write gap field to rise fully within one bit cell; this ensures linear super-position of the recorded transitions. The post-equalization is then designed to yield flat amplitude, constant group delay response for the complete channel. This sequence results in output waveforms which are as close as possible replicas of the input Miller² waveforms. Clearly, this minimizes the loss of information through the channel.

In the bit error rate data below a standard coercive force γ-$Fe_2 0_3$ video tape was used. Two differently phased pseudo-random Miller² coded words at 15 Mbs per channel were used. During each swipe across the tape about 36,000 bits were recorded on each track.

In Table 1, we show a histogram of the error counts found for two adjacent tracks of a multi-channel saw-cut ferrite head of the type described earlier. Some 30,000 swipes were recorded on erased tape and read once only; in total, some 2200 Mbits of data were monitored.

	Track 1	Track 2
No. of Swipes with Zero Errors	29909	29935
" " " " 1 "	56	38
" " " " 2 "	24	15
" " " " 3 "	7	1
" " " " 4 "	3	6
" " " " 5 "	1	5
" " " " over 5 "	0	0
Total Bits in Error	142	120
BER, Bits Per Error	7.7×10^6	9.2×10^6

Table I Histogram of Errors in 2200 Mbits

It will be noted that on this tape almost no large "dropouts" occur; no error bursts larger than 5 bits were detected. The overall BERs are in the region of 10^7 bits per error, rather better than the target.

It is our experience that an extremely wide variation in tape quality exists even within a particular category of tape product. For example, some high energy ($H_C \approx 500 - 600$ Oe) helical video tapes, having perhaps 5 – 6 dB greater SNR than conventional tape, yield BERs worse by factors of ten. It appears that in extremely high density digital recording, the state of physical perfection (freedom from defects, dirt, etc.) is of as great importance as the SNR.

CONCLUSIONS

Considerable progress has been made in the fabrication of micro-miniature multi-channel head stacks using both conventional and thin film techniques. The performance of AST systems are adequate to provide accurate tracking of 1 mil wide tracks at any data rate below the maximum. Magnetic tapes of sufficient physical perfection to yield BERs greater than 10^6 are commercially available. A 1000 Mbs recorder is technically possible and would be a machine of much the same size and complexity as a broadcast quality video recorder.

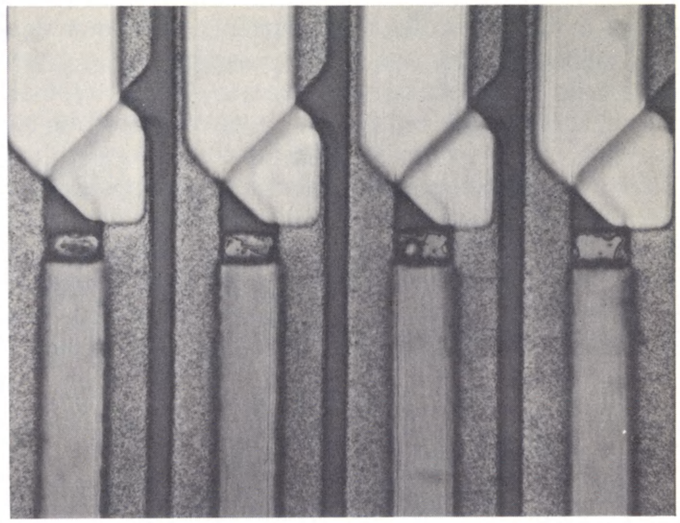


Figure 3 Several 1 Mil Trackwidth Thin Film Head Pole Tips

ACKNOWLEDGEMENTS

Many individuals have contributed outstandingly to this project. Particular commendation is due to Bill Baker, Michael Felix, Jerry Lundquist and John Watney.

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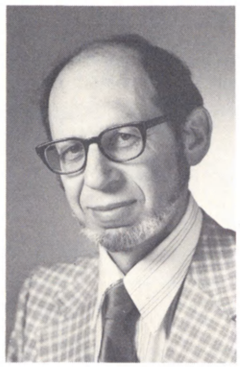
Numerical solution of the planar hydrostatic foil bearing

BY ABE ESHEL



ABE ESHEL is a member of the research staff in the advanced technology division of Ampex Corporation and has been working on mathematical and experimental modeling of mechanical problems in magnetic recording since joining the company in 1966. He has been involved in projects for the simulation of air lubrication of magnetic heads in the super HBR system, simulation of head impact in the VPR recorders, tape guiding, cartridges and vacuum columns. Abe holds a doctorate in engineering from Columbia University.

Externally pressurized foil bearings have found many applications in the tape recording and manufacturing industries. They are useful wherever it is important to prevent a travelling web from contacting guides or walls. Despite their utilization over the past two decades, not all aspects of their behavior are well understood.

The case of the axisymmetric hydrostatic foil bearing was studied by Barlow.[1] In this case, only side flow was assumed to prevail in the bearing. The problem of a planar hybrid foil bearing in which hydrodynamic effects dominate was studied.[2-4] Here hydrostatic effects merely modify the essentially hydrodynamic bearing characteristics. During start up conditions, however, the foil is supported hydrostatically. It is useful, therefore, to be able to predict the minimum film thickness during this phase of operation. This problem, namely, the planar, purely hydrostatic foil bearings, is, therefore, the subject of the present paper.

The initial goal of this investigation was, actually, to illustrate the applicability of a preprocessor computer program for the automatic solution of partial differential equations. Ironically, it turned out, the automatic solution was only partly successful and numerical difficulties were encountered in certain parameter ranges, requiring some human intervention. Consequently, an alternative approach was utilized and a complete set of data curves generated. It is felt, however, that the numerical experience gained in this effort as well as the concepts of the preprocessor are of interest and, therefore, they are reported here as well as the solution of the particular problem at hand.

HYDROSTATIC FOIL BEARING MODEL

Let the configuration shown in Figure 1 be studied. Here, an infinitely wide, hydrostatic, cylindrical, perfectly flexible foil bearing with incompressible lubricant is depicted schematically. In this configuration, one line feed source is located at $\theta = \theta_g$. A second line source is symmetrically situated at the other side of the bearing. It is assumed that the feed pressure p_g is prescribed and maintained constant. The film thickness and pressure are, then, governed by the following differential equations:

$$\frac{\partial}{\partial \theta}\left(h^3 \frac{\partial p}{\partial \theta}\right) = 12\mu r_0^2 \frac{\partial h}{\partial t} \tag{1}$$

$$p - p_a = \frac{T}{R} = \frac{T}{r_0}\left(1 - \frac{1}{r_0}\frac{\partial^2 h}{\partial \theta^2} + \ldots\right) \tag{2}$$

Using the dimensionless representation

$$\bar{h} = \frac{h}{r_0}$$

$$\Pi = \frac{p - p_a}{T/r_0}$$

and restricting the problem to steady state, equations (1), (2) may be rewritten as

$$\bar{h}^3 \frac{\partial \Pi}{\partial \theta} = -\frac{12\mu Q}{r_0 T} \tag{3}$$

$$\Pi = 1 - \frac{\partial^2 \bar{h}}{\partial \theta^2} + \ldots \tag{4}$$

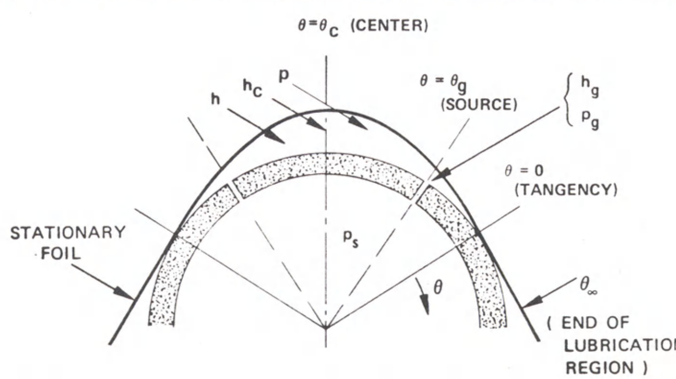


Figure 1 Cylindrical hydrostatic foil bearing

where Q is an integration constant representing the volume flow rate per unit width. Equations (3), (4) may be combined to:

$$\bar{h}^3 \frac{\partial^3 \bar{h}}{\partial \theta^3} = \epsilon + \ldots \tag{5}$$

where the dimensionless flow rate ϵ is defined by

$$\epsilon = \frac{12\mu Q}{r_0 T}$$

It may be observed that under steady conditions there is no flow in the region $\theta_c \leqslant \theta < \theta_g$ (due to symmetry we restrict our treatment to one half of the problem). The pressure in this region is, therefore, uniformly $p = p_g$. In dimensionless form:

$$\Pi = \Pi_g \equiv \frac{p_g - p_a}{T/r_0}$$

The boundary conditions are:

$$\text{At } \theta = \theta_g \qquad \bar{h}, \bar{h}' \text{ and } \Pi \text{ are continuous} \tag{6}$$

$$\text{As } \theta \to \frac{\pi}{2} \qquad p \to p_a \tag{7}$$

$$\bar{h} \to \frac{1 + \bar{h}_a}{\cos\theta} - 1 \tag{8}$$

Condition (8) specifies that the foil approaches an asymptote located at some small unknown dimensionless distance h_a away from the point of tangency. This unknown may be eliminated from equation (8) by differentiation.

Consider now a hypothetical process in which the tension is gradually increased while θ_c, θ_g, $p_g - p_a$, r_0, μ remain unchanged. One anticipates a corresponding reduction of flow, or of ϵ. (Note that this process implies either a change in restriction or in the source pressure, to maintain a constant p_g despite changes in Q.) Following a derivation analogous to reference [5] one assumes

$$H = \frac{\bar{h}}{\epsilon^n} \tag{9}$$

$$\xi = \frac{\theta}{\epsilon^m} \tag{10}$$

The following requirements may be imposed: The two sides of equation (5) must balance as $\epsilon \to 0$; hence,

$$4n - 3m = 1 \tag{11}$$

Secondly, at least one variable term in equation (2) must not vanish as $\epsilon \to 0$; hence,

$$n - 2m = 0 \tag{12}$$

It follows then, that

$$m = 1/5 \tag{13}$$

$$n = 2/5 \tag{14}$$

Thus, in the region $\xi_c \leqslant \xi < \xi_g$

$$\frac{d^2H}{d\xi^2} = 1 - \Pi_g \tag{15}$$

$$\frac{dH}{d\xi} = (1 - \Pi_g)(\xi - \xi_c) \tag{16}$$

$$H = \frac{1}{2}(1 - \Pi_g)(\xi - \xi_c)^2 + H_c \tag{17}$$

where H_c is the unknown dimensionless film thickness at $\xi = \xi_c$.

The formulation of the problem in region $\theta_g < \theta$ becomes

$$H^3 \frac{d^3H}{d\xi^3} = 1 \tag{18}$$

$$\left.\frac{dH}{d\xi}\right|_{\xi = \xi_g} = (1 - \Pi_g)(\xi_g - \xi_c) \tag{19}$$

$$\left.\frac{d^2H}{d\xi^2}\right|_{\xi = \xi_g} = 1 - \Pi_g \tag{20}$$

$$\left.\frac{dH}{d\xi}\right|_{\xi \to \infty} \sim \xi \tag{21}$$

$$\left.\frac{d^2H}{d\xi^2}\right|_{\xi \to \infty} \sim 1 \tag{22}$$

The fact that we have four boundary conditions for a third order equation indicates that one of the parameters of the problem is not free. The following functional form is, therefore, deduced:

$$\Pi_g = f\left(\frac{\theta_g}{\theta_c}, \xi_c\right) \tag{23}$$

$$H = f\left(\xi; \frac{\theta_g}{\theta_c}, \xi_c\right) \tag{24}$$

The solution techniques are discussed in the appendix.

RESULTS AND DISCUSSION

The results are summarized in Figures 2–5. They are expressed in terms of two dimensionless parameters, namely: θ_g/θ_c specifying the source location, and $(12\mu Q/r_0 T)^{1/5}/|\theta_c|$ describing flow rate. Figure 2 illustrates some typical tape contours while Figures 3–5 present the dimensionless groove pressure and some characteristic film thicknesses.

The basic behavior of the bearing as it appears from these graphs may be described by means of a conceptual experiment. In this experiment, $p_g - p_a$ is slowly increased while the geometry and tension remain constant. The

changes in radius of curvature of the foil that take place in the wrap region during this process are described below. These changes result from a compromise between two competing effects. On the one hand, the effect of a decrease in film thickness is to increase the tape-to-cylinder conformity. In other words, the foil radius of curvature tends to r_0 as Q and $h(\theta)$ vanish. Thus, $p_g - p_a$ approaches T/r_0 and Π_g approaches unity. On the other hand, despite the smallness of $h(\theta)$ for low Q, the foil in the region of wrap (Figure 2) has a "bubble" shape typified by a large ratio of h_c/h_t. Qualitatively, the effect of this ratio being different from unity is to cause the foil radius of curvature to deviate from that of the cylinder. When Q increases, $h(\theta)$ increases, thus weakening the sealing effect of the foil at the point of tangency. In this case, the ratio of h_c/h_t decreases, goes through unity and eventually becomes less than unity. Correspondingly, the foil radius of curvature starts at r_0 (for $h \to 0$), decreases for higher Q, bottoms out and finally rises above r_0. This is manifested by the curves of Figure 3 and explains the reason for the double valuedness of Π_g.

The analysis presented above assumes that p_g may be controlled independently of Q. In any practical situation, the restrictor characteristic presents a curve of p_g versus Q, which may be superimposed on Figure 3. The intersection determines possible operating points which are schematically illustrated in Figure 6.

Neglecting the effect of damping which may be brought out only by a dynamic analysis, it may be speculated that intersections of type A, C tend to be stable whereas intersections of type B tend to be unstable. The argument is essentially as follows. Considering point B for example, an upward fluctuation in flow, reduces p_g. This in turn tends to push the operating point further away from B by causing a net outflow from the bearing. Similar arguments indicate the stability of A and C.

Another observation of interest is that $\theta_g/\theta_c \approx 0.05$ is a threshold value, below which contact between the tape and the cylinder may arise. In these situations the source is located too close to the point of tangency for useful operation. When the flow is minute, a non-contact situation is possible. For slightly higher flow rates, the seal effect at the tangency point disappears and flotation of the foil cannot be maintained throughout the wrap angle.

Theoretical predictions have been made of the behavior of planar, incompressible, hydrostatic foil bearings, neglecting the effects of fluid inertia. Efforts are in progress to remove these restrictions and to compare the results with experiment.

NOMENCLATURE

G = constant found from the solution of equation (25)
h = local film thickness
$\bar{h}$ = dimensionless film thickness h/r_0
$\bar{h}_a$ = dimensionless distance of foil asymptote to cylinder
H = stretched film thickness coordinate
$\bar{H}$, $\hat{H}$ = auxiliary normalized values of H for computational purposes
m, n = exponents, to be determined
p = local pressure in film
p_a = ambient pressure
Q = volume flow rate per unit bearing width
R = local radius of curvature
r_0 = cylinder radius
t = time
T = foil tension per unit width
$\epsilon = \dfrac{12\mu Q}{r_0 T}$ dimensionless flow rate
μ = gas viscosity
Π = dimensionless pressure
θ = angular coordinate (origin at point of tangency)
τ = dimensionless time
ξ = stretched angular coordinate
$\bar{\xi}$, $\hat{\xi}$ = auxiliary normalized values of ξ for computational purposes

SUBSCRIPTS

c = pertains to cylinder center
g = pertains to source location (groove)
t = pertains to point of tangency
∞ = pertains to end of lubrication zone

APPENDIX I: PREPROCESSOR SOLUTION

With present-day powerful computers, the engineer has at his disposal an invaluable tool for optimization and evaluation of design parameters. Frequently, this evaluation is based on numerical simulation of the behavior of a physical model represented by a partial differential equation. In order to perform the simulation, it becomes necessary, in such cases, to discretize the partial differential equation and to write a computer program that will solve the resulting difference equation and print or display the results numerically and/or graphically. This task is, often, time-consuming and usually requires several debugging runs.

Though laborious, this programming effort, commonly, consists of rather similar subtasks. In general, the programming job may be described as the insertion of problem dependent details into a basic program template designed for the particular algorithm and a broad class of equations. Consequently, it is feasible to carry out this process, too, with the aid of the computer. This is done by means of a preprocessor or a precompiler. The precompiler is a computer program which accepts an input describing the partial differential equation and its boundary conditions in a concise and readable mathematical symbolism, and outputs a high level language (e.g., PLI) program which is then compiled by the language compiler just like a human-written program. The compiler-generated object program is finally executed (Figure A1).

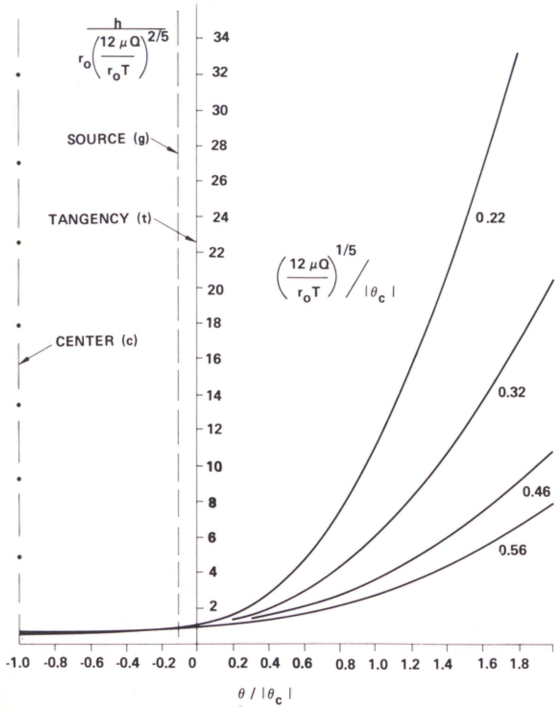


Figure 2(a) Tape contours for a range of flow rates with $\theta_g/\theta_c = 0.1$

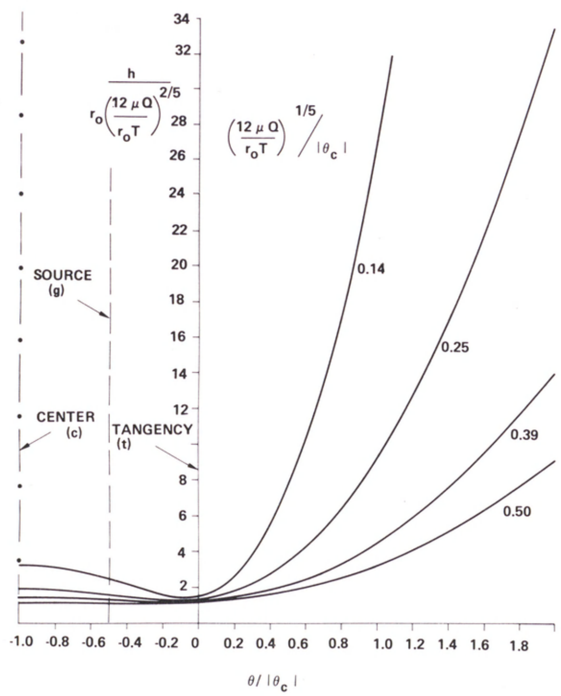


Figure 2(b) Tape contours for a range of flow rates with $\theta_g/\theta_c = 0.5$

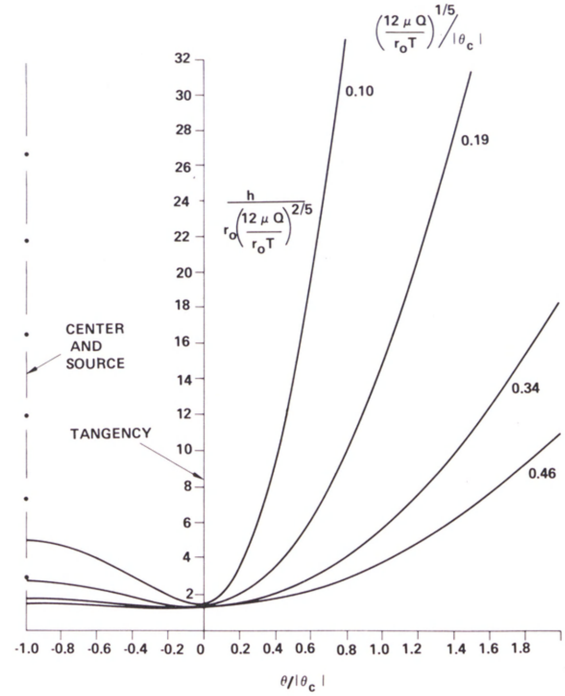


Figure 2(c) Tape contours for a range of flow rates with $\theta_g/\theta_c = 1.0$

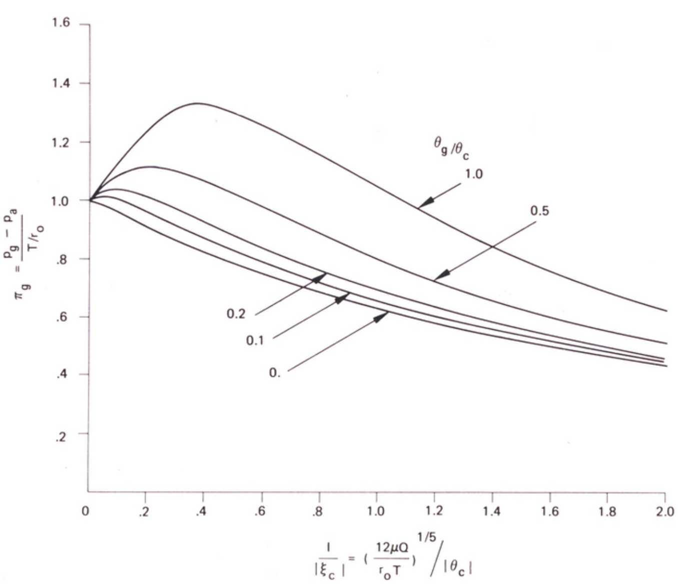


Figure 3 Dimensionless pressure drop versus dimensionless flow rate across foil bearing

In this paper, we would limit the discussion to a precompiler for the class of parabolic, high order, one dimensional partial differential equations. We will restrict ourselves, further, to the implicit solution algorithm. This class of problems is still rather broad; and in particular, it is applicable to many foil-bearing problems.

FORMULATION

In order to allow solution by means of a program generated by our precompiler for parabolic partial differential equations, the formulation (18)–(22) for H and Π_g will be replaced by the following alternative formulation defining a function $H(\xi, \tau)$. H will later be transformed to

the desired function $H(\xi)$.

$$-\frac{\partial^4 \overline{H}}{\partial \overline{\xi}^4} \cdot \overline{H}^3 - \frac{\partial^3 \overline{H}}{\partial \overline{\xi}^3} 3\overline{H}^2 \frac{\partial \overline{H}}{\partial \overline{\xi}} = \frac{\partial \overline{H}}{\partial \tau} \tag{25}$$

$$\overline{H} \Big|_{\xi = \xi_g} = \overline{H}_g \tag{26}$$

$$\frac{\partial \overline{H}}{\partial \overline{\xi}^2} \cdot (\overline{\xi}_g - \overline{\xi}_c) - \frac{\partial \overline{H}}{\partial \overline{\xi}} \Big|_{\overline{\xi} = \overline{\xi}_g} = 0 \tag{27}$$

$$\frac{\partial \overline{H}}{\partial \overline{\xi}} \Big|_{\overline{\xi} = \overline{\xi}_\infty} \sim \xi \tag{28}$$

$$\frac{\partial^2 \overline{H}}{\partial \overline{\xi}^2} \Big|_{\overline{\xi} = \overline{\xi}_\infty} \sim 1 \tag{29}$$

When a steady state solution, $\overline{H}(\overline{\xi};\, \overline{\xi}_g/\overline{\xi}_c,\, \overline{\xi}_c,\, \overline{H}_g)$ satisfying these requirements is obtained, a parameter G, elaborated upon later, may be evaluated from

$$G = H^3 \frac{\partial^3 H}{\partial \overline{\xi}^3} \tag{30}$$

$H(\xi)$, H_c, ξ_c, and Π_g may then be obtained from the numerical solution obtained by the transformations

$$H = \overline{H}/G^{2/5} \tag{31}$$

$$\xi = \overline{\xi}/G^{1/5} \tag{32}$$

$$\Pi_g = 1 - \frac{\partial^2 \overline{H}}{\partial \xi^2} \Big|_{\xi = \xi_g} \tag{33}$$

$$H_c = \overline{H}_g - \frac{1}{2}(1 - \Pi_g)(\xi_g - \xi_c)^2 \tag{34}$$

Substitution of the transformations (31)–(34) into equations (25)–(29) will verify that the function H indeed satisfies all the requirements (18)–(22). The equality of the ratios $\overline{\xi}_g/\overline{\xi}_c$, ξ_g/ξ_c, θ_g/θ_c simplifies the presentation of the results.

The value of G, though theoretically a constant, may be expected to vary somewhat with ξ due to truncation and round-off errors in the solution. It was rather unexpected, however, to find that in certain parameter ranges unacceptable nonuniformities in G were found numerically. However, for those parameter values for which the values of G were sufficiently uniform, the results agreed very well with those of the alternative technique described below.

The input into the precompiler is illustrated in Figure A2. Further details about the precompiler are given in [6].

APPENDIX II: O.D.E. SOLUTION

Let equations (18)–(22) be reformulated in terms of alternative variables $\hat{H}(\hat{\xi})$, in order to permit solution as an initial value problem. Later the solution for $\hat{H}$ will be transformed back into $H(\xi)$. The reformulated problem is:

$$\hat{H}^3 \frac{d^3 \hat{H}}{d\hat{\xi}^3} = 1 \tag{35}$$

At $\hat{\xi} = 0$

$$\hat{H} = \hat{H}_g \tag{36}$$

$$\hat{H}' = \hat{H}_g' \tag{37}$$

$$\hat{H}'' = \hat{H}_g'' \tag{38}$$

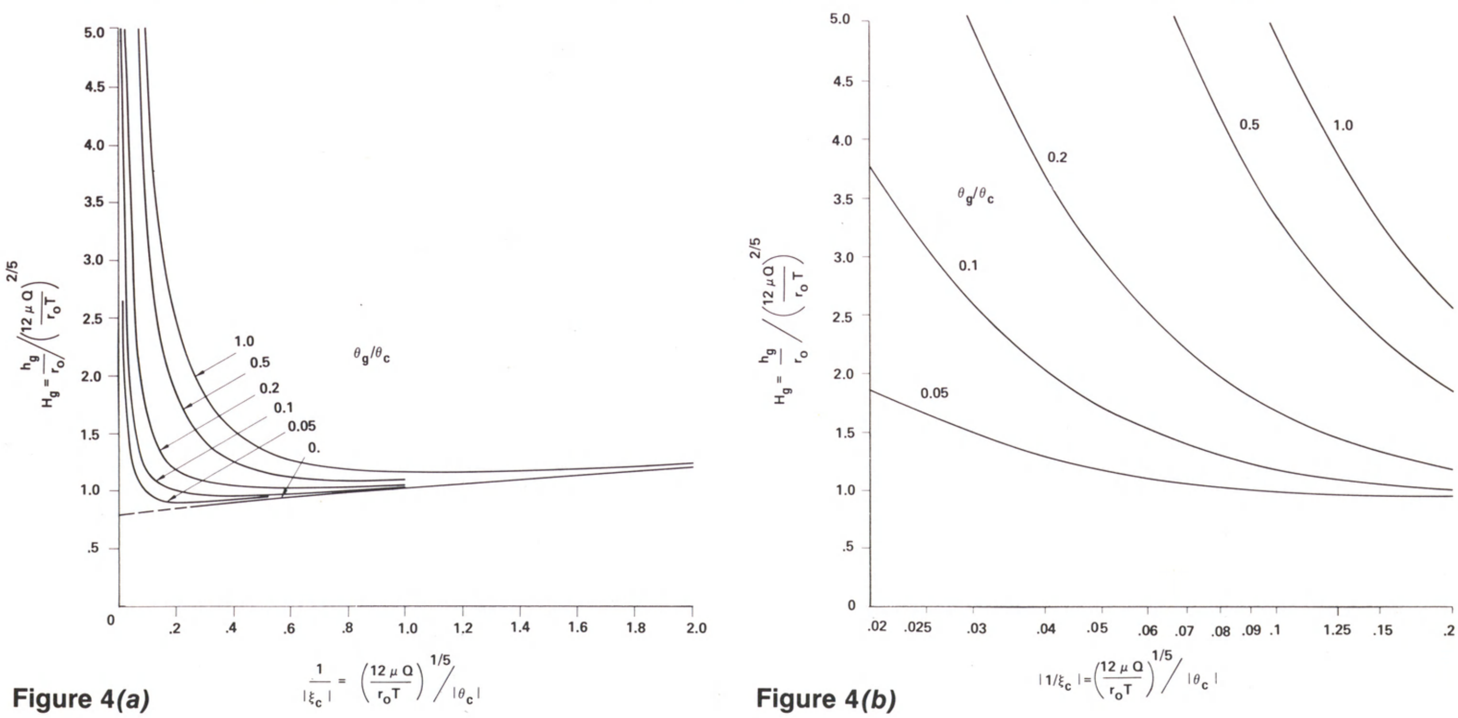


Figure 4*(a)*

Figure 4*(b)*

Figure 4 Dimensionless film thickness at supply groove versus dimensionless flow rate

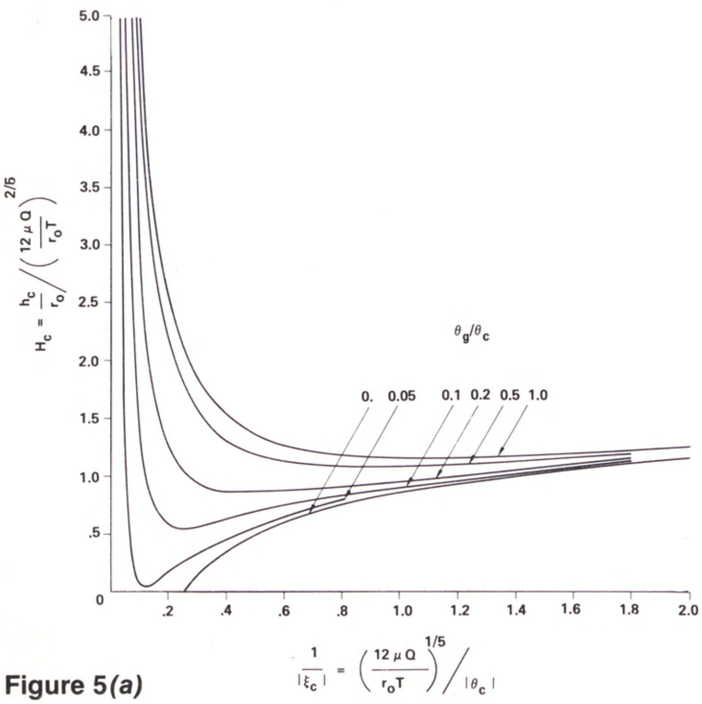


Figure 5*(a)*

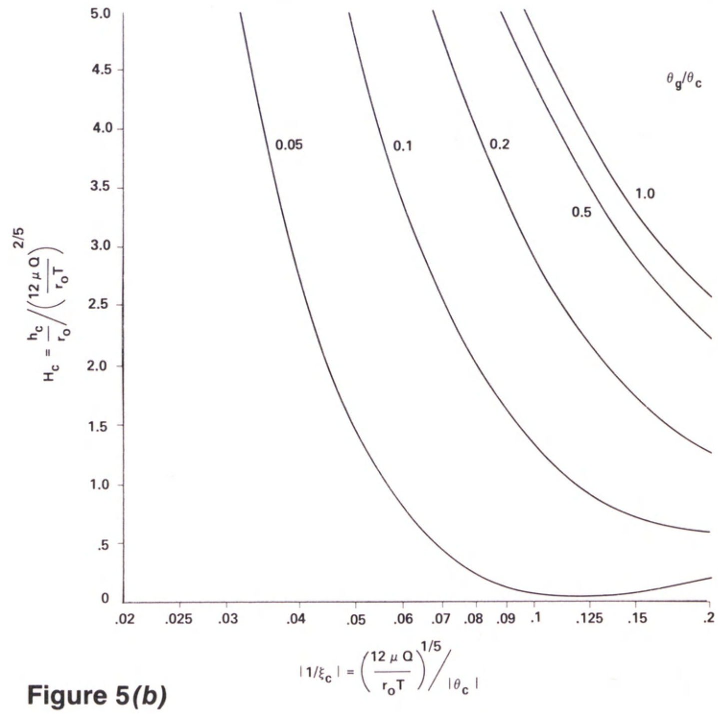


Figure 5*(b)*

Figure 5 Dimensionless film thickness at cylinder center versus dimensionless flow

Integration as an initial value problem is terminated when $\hat{H}''$ tends to approach a constant say $\hat{H}_\infty''$. The exact termination value is not critical, but it should be sufficiently large so that $\hat{H}_\infty/\hat{H}_g >> 1$. It may be verified that the conversion

$$H = H \cdot (H_\infty'')^{3/5}$$

$$\xi = \left(\hat{\xi} - \hat{\xi}_\infty + \frac{\hat{H}_\infty'}{\hat{H}_\infty''}\right) \cdot (\hat{H}_\infty'')^{4/5}$$

transforms the solution aposteriori to that of the original coordinates. The parameters of the problem which has been solved are found by:

$$\Pi_g = 1 - \hat{H}_g''/\hat{H}_\infty''$$

$$\xi_g = \hat{H}_\infty'/\hat{H}_\infty''^{1/5} - \hat{\xi}_\infty \hat{H}_\infty''^{4/5}$$

$$\xi_c = \hat{H}_\infty'/\hat{H}_\infty''^{1/5} - \hat{H}_\infty''^{4/5}(\hat{H}_g'/\hat{H}_g'' + \hat{\xi}_\infty)$$

$$H_c = H_g - \frac{1}{2}(1 - \Pi_g)(\xi_g - \xi_c)^2$$

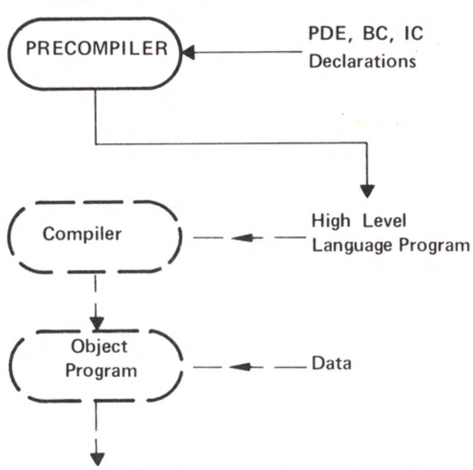


Figure A1 Schematic view of the role of the precompiler in problem solution. (Broken lines indicate conventional computer solution. Solid lines add the effect of the precompiler.)

```
EXTP:  PROCEDURE OPTIONS (PARABOLIC);
       /* EXTERNALLY PRESSURIZED FOIL BEARING ANALYSIS.
       STATIONARY, INCOMPRESSIBLE, PLANAR, PERFECTLY
       FLEXIBLE, REFERENCED TO A CYLINDRICAL SURFACE.
       TWO SOURCES, SYMMETRICALLY LOCATED ABOUT CENTER.  */
              DECLARE
       XIC    PARAMETER,  /* COORDINATE OF CENTER  */
       XIR    PARAMETER,  /* XIG/XIC , WHERE XIG=COORDINATE OF SOURCE  */
       XI8    PARAMETER,  /* COORDINATE, END OF LUBRICATION ZONE  */
       HG     PARAMETER,  /* H VALUE AT SOURCE  */
       HMIN   PARAMETER;  /* INITIAL VALUE OF H AT TANGENCY POINT  */
              DECLARE
       X     INDEPENDENT(1), /* 1ST VARIABLE IN LIST, SPATIAL COORDINATE  */
       T     INDEPENDENT(2), /* 2ND VARIABLE IN LIST, TIME COORDINATE  */
       H     DEPENDENT: /* DIMENSIONLESS FILM THICKNESS, H_BAR IN PAPER  */
DE:                           @4X(H) * (-H**3) + @3X(H) * (-3.*H**2 * @X(H)) = @T(H);
BC LOW (XIR*XIC,*):  H=HG;
BC LOW (XIR*XIC,*):  @2X(H)*(XIR-1.)*XIC+@X(11)*(-1.)=0.;
BC HIGH (XI8),*):     @X(H)=XI8;
BC HIGH (XI8),*):     @2X(H)=1.;
IC:                   H=HMIN+X**2/2.;
          END;
```

Figure A2 Precompiler input (corresponding to equations (25)–(29))

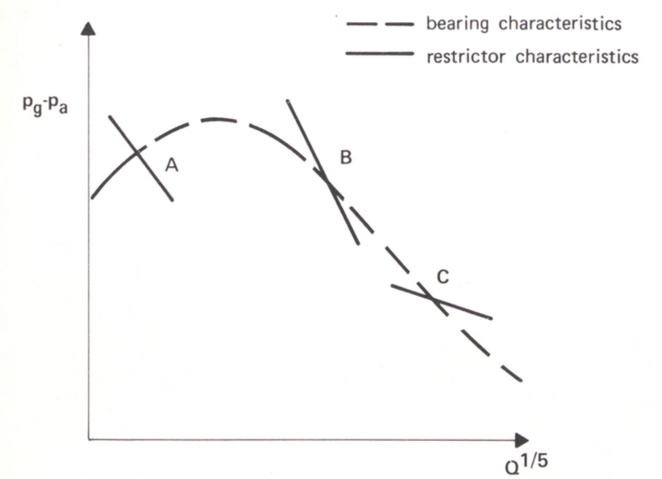


Figure 6 Schematic view of various possibilities of operating points

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